The FNAL/NICADD photoinjector laboratory: current status and prospects towards a linear collider test facility at FNAL

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FNAL/NICADD Photo-injector Laboratory

NIU, Nov 19th, 2004

http://nicadd.niu.edu/fnpl

Outline

- Introduction: Some basics on beams
- Requirement on electron beam for linear colliders and linac-based light sources
- The FNPL facility
  - overview
  - recent achievement and short term plans
  - energy upgrade and associated program
- The SM&TF proposal
- Summary

Introduction I

- Application of high-brightness photo-injectors:
  - high energy linear colliders (needs flat beam $\varepsilon_y/\varepsilon_x$ <<1)
  - radiation sources (FELs, short pulse , high power)
  - X-rays production (XTR, Thomson)
  - plasma-based electron sources-drivers,
  - etc
- Many accelerator test facilities in operation based on photo-injectors:
  - dedicated to beam physics (BNL, UCLA, DESY-Z, NERL...)
  - drive user-facility (ATF, Jlab, DESY-HH,…)
- Figure-of-merit: emittance (FELs requires $\varepsilon<\lambda$) , peak current, average current (photon flux), local energy spread, bunch length (e.g. for probing ultra-fast phenomena)…

Introduction II: Note on emittance

Canonical emittance (Liouvillian invariant under linear force)

What codes give

$$\varepsilon_{CAN} = \frac{1}{m_e c}\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle x\, p_x\rangle^2}$$

Or, $p_x(i) = p_z(i)\, x'(i) = \langle p_z\rangle\left[1+\delta(i)\right] x'(i)$

$$\varepsilon_{CAN} = \frac{\langle p_z\rangle}{m_e c}\sqrt{\langle x^2\rangle\langle(1+\delta)^2 x'^2\rangle - \langle(1+\delta)\, x\, x'\rangle^2}$$

Trace-space normalized emittance (experimental observable)

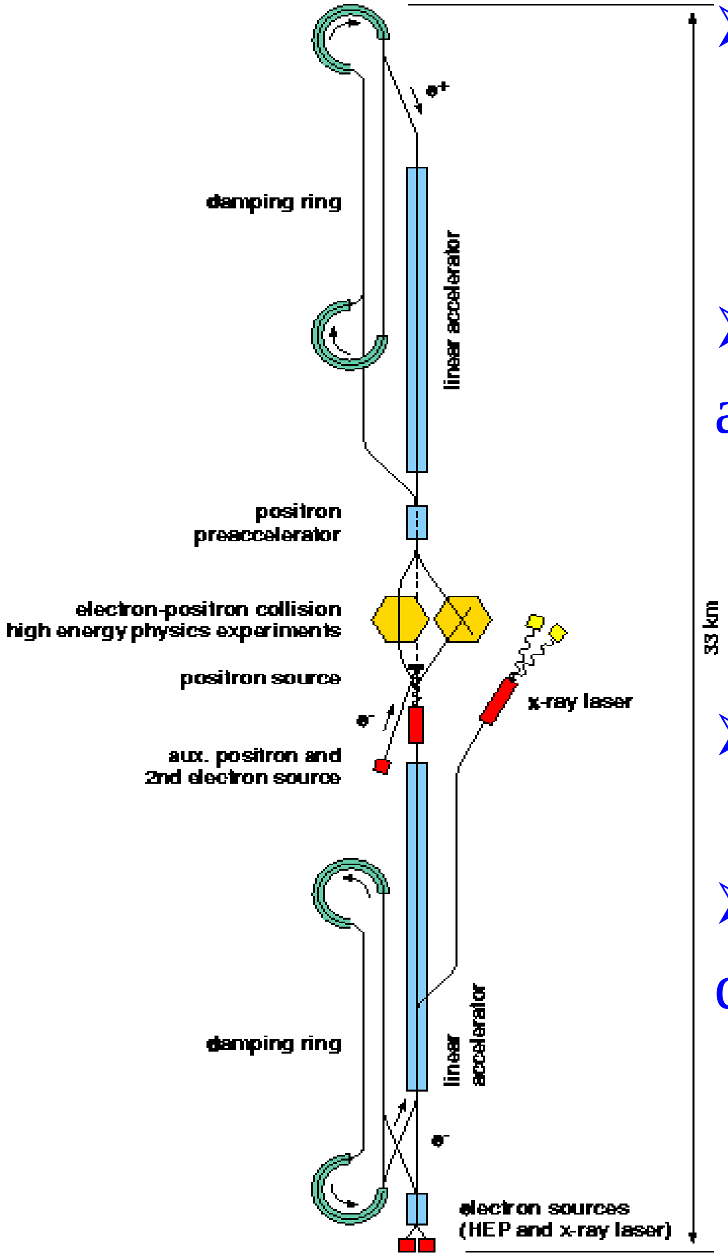
$$\varepsilon = \beta\,\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x\, x'\rangle^2}$$

Might be different if large fractional momentum spread

Beam brightness $\quad B = \dfrac{Q}{\tau_6} = \dfrac{Q}{\varepsilon_x \varepsilon_y \varepsilon_z}$

6-d hypervolume

e^+e^- linear colliders requirements



- Figure-of-merit is luminosity

$$L = \frac{P_b}{E_{CM}} \frac{N_e}{4\pi\sigma_x\sigma_y} H_D$$

- Beamstrahlung impose the choice of a large aspect ratio at the IP $(\sigma_x \gg \sigma_y)$

$$\delta_E \propto \frac{N_e^2 \gamma}{\sigma_z(\sigma_x + \sigma_y)}$$

- Make σ_y as small as possible

- Reduction of transverse emittances usually done in damping ring (radiative cooling)

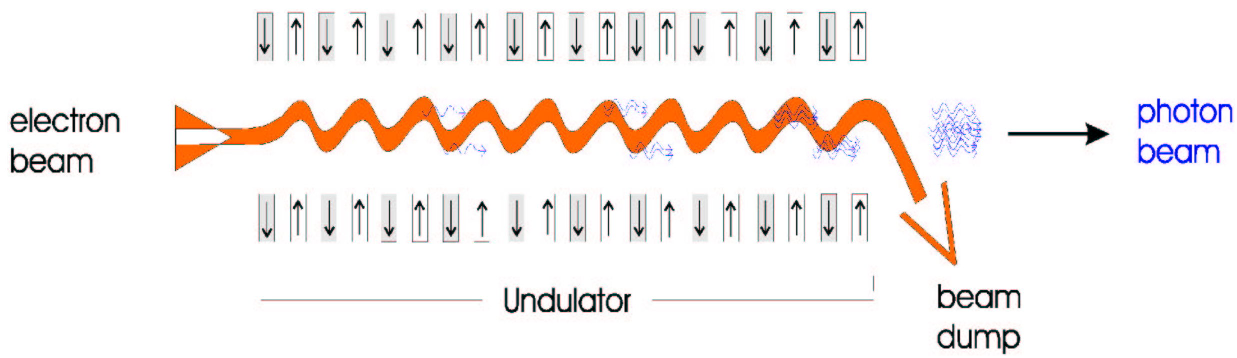
Linac-based light source requirements

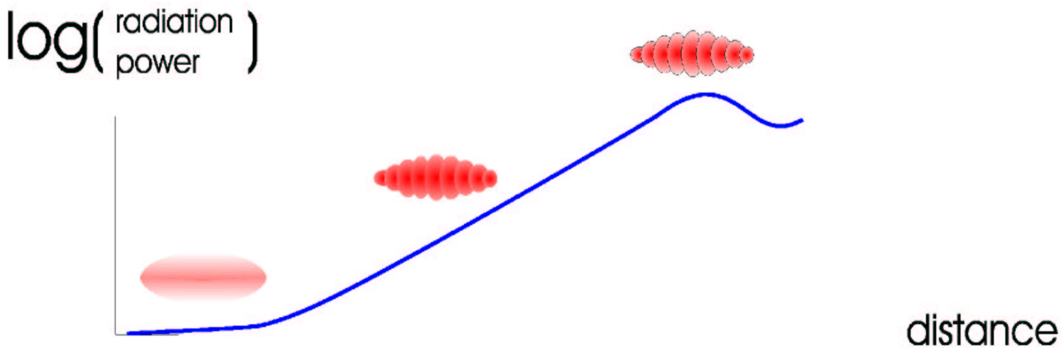
➢Electron linac can be use to drive free-electron laser

➢The so-called high gain single pass FEL can generate ultrashort VUV or X-ray pulses

➢The demand on the electron beam is stringent $\varepsilon_{unorm} < \lambda$

Multi kA peak current

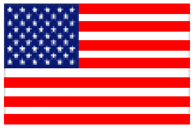




FNAL/NICADD photo-injector Laboratory

- FNPL is a collaborative effort amongst several institutes and universities to operate a high-brightness electron photo-injector dedicated to fundamental and advanced accelerator R&D
- Main support comes from FNAL & North Illinois Center of Accelerator & Detector Development (NICADD)

- Collaborators includes:



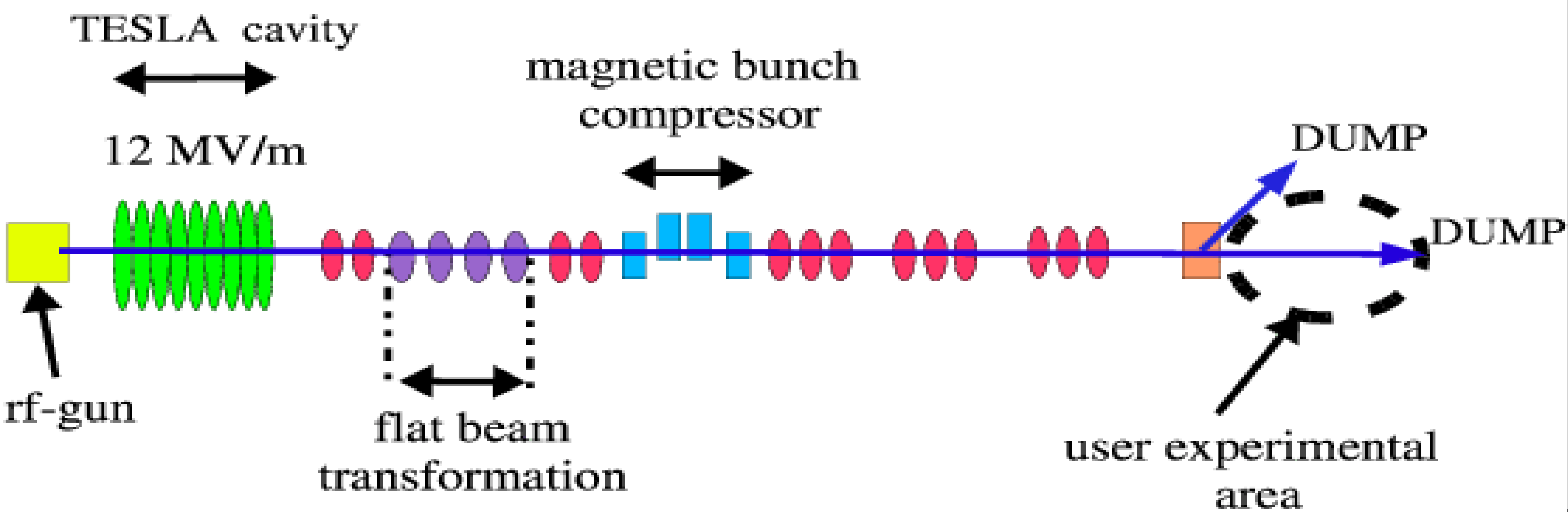
U. of Chicago, U. of Rochester, UCLA,
U. of Indiana, U. of Michigan, LBNL, NIU,
U. of Giorgia, ANL, Cornell University

DESY, INFN-Milano, IPN-Orsay
CEA-Saclay

FNAL/NICADD photo-injector Laboratory

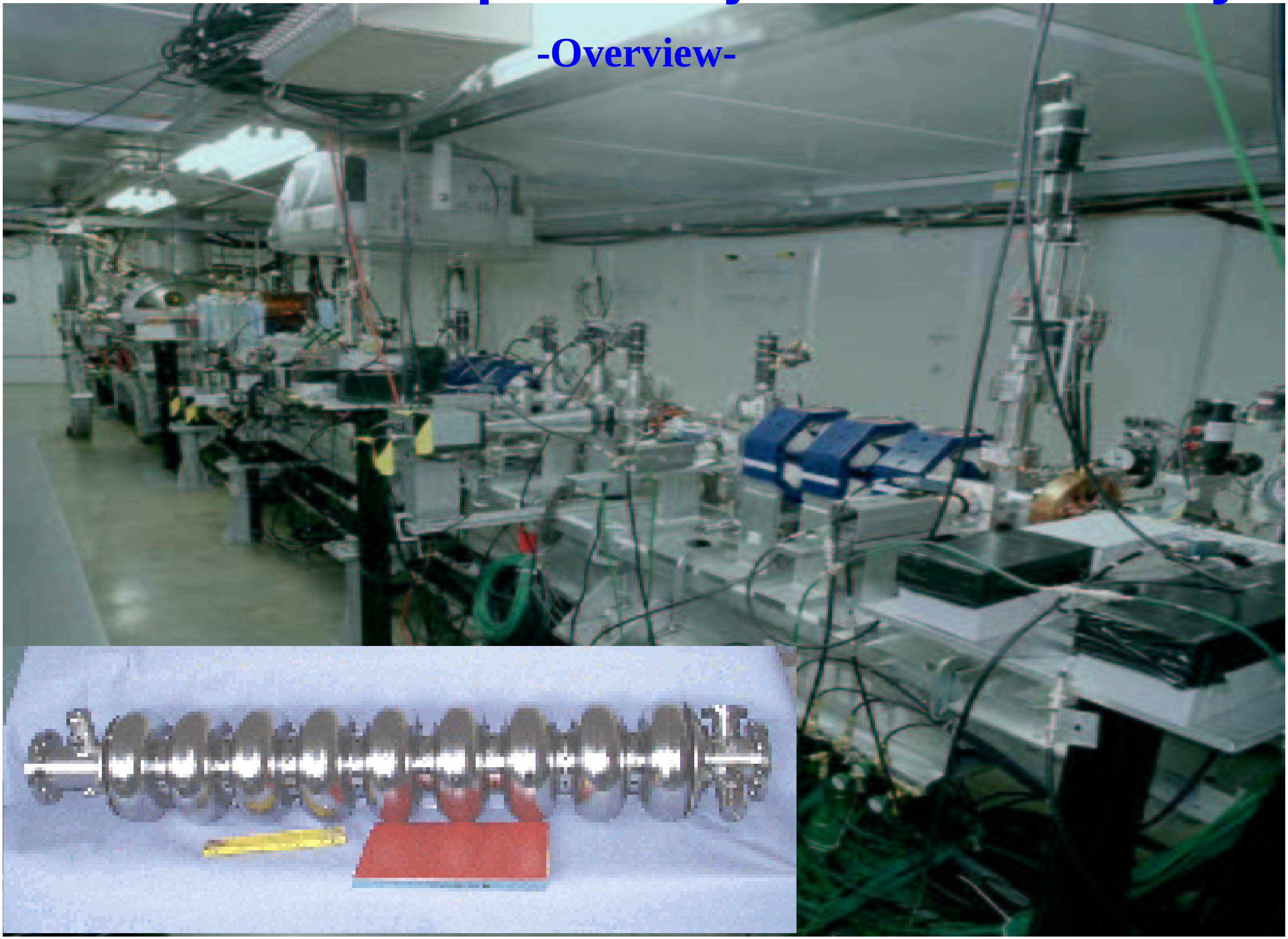
-Overview-

- Photo-emission electron source
- A TESLA cavity operating at 12 MV/m
- Quads, correctors magnets, dipoles and extensive diagnostics (OTR and YaG-based screens, electromagnetic beam position monitors)
- Bunch compression possible with a magnetic chicane
- User area accommodates experiment [at the moment plasma-wakefield trapping experiment]



FNAL/NICADD photo-injector Laboratory

-Overview-

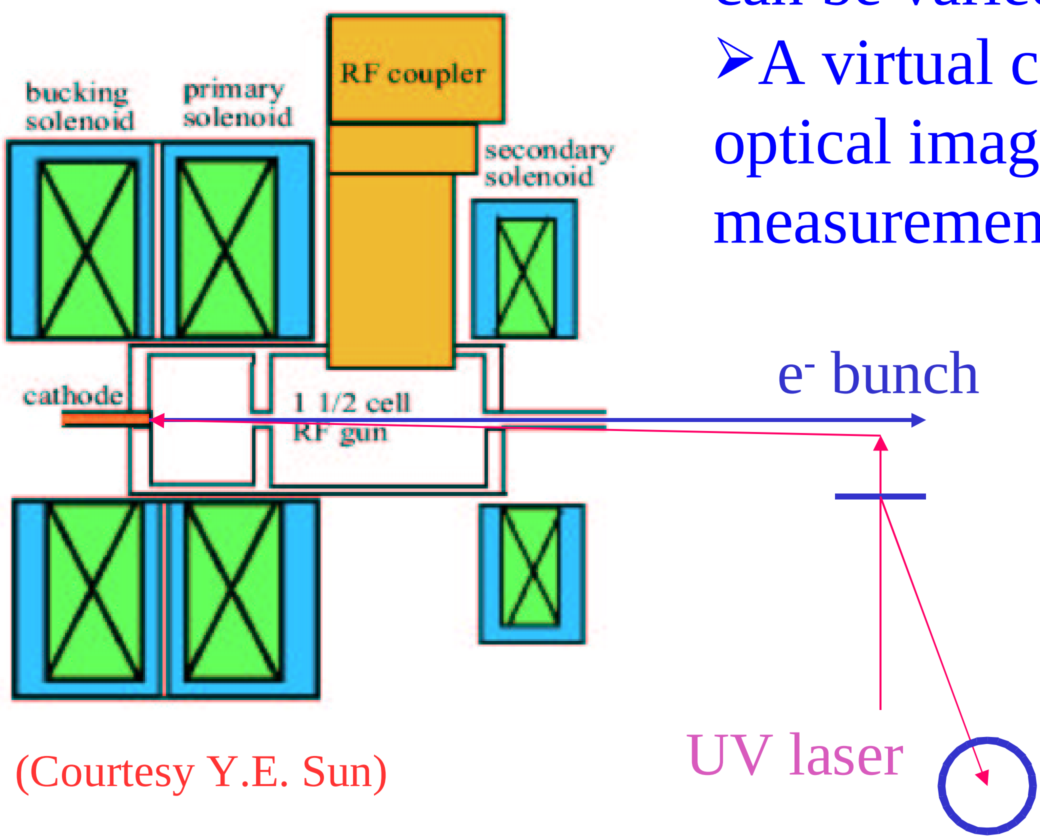


FNAL/NICADD photo-injector Laboratory

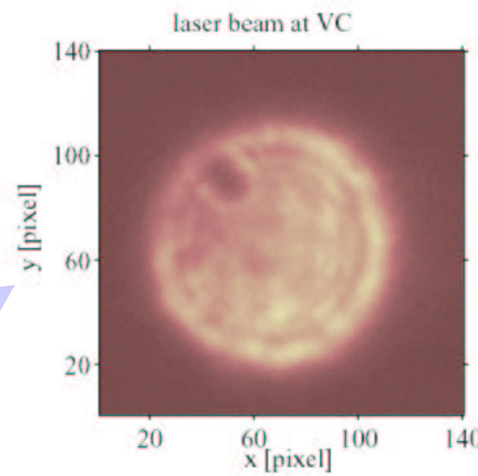
-the photo-emission electron source-

- High quantum efficiency photo-cathode (Cesium Telluride)
- A 1.3 Ghz rf-gun
- Three solenoids with independent power supply

- Initial conditions (laser spot size, intensity can be varied)
- A virtual cathode being an one-to-one optical image of the photocathode provide measurements of initial laser size

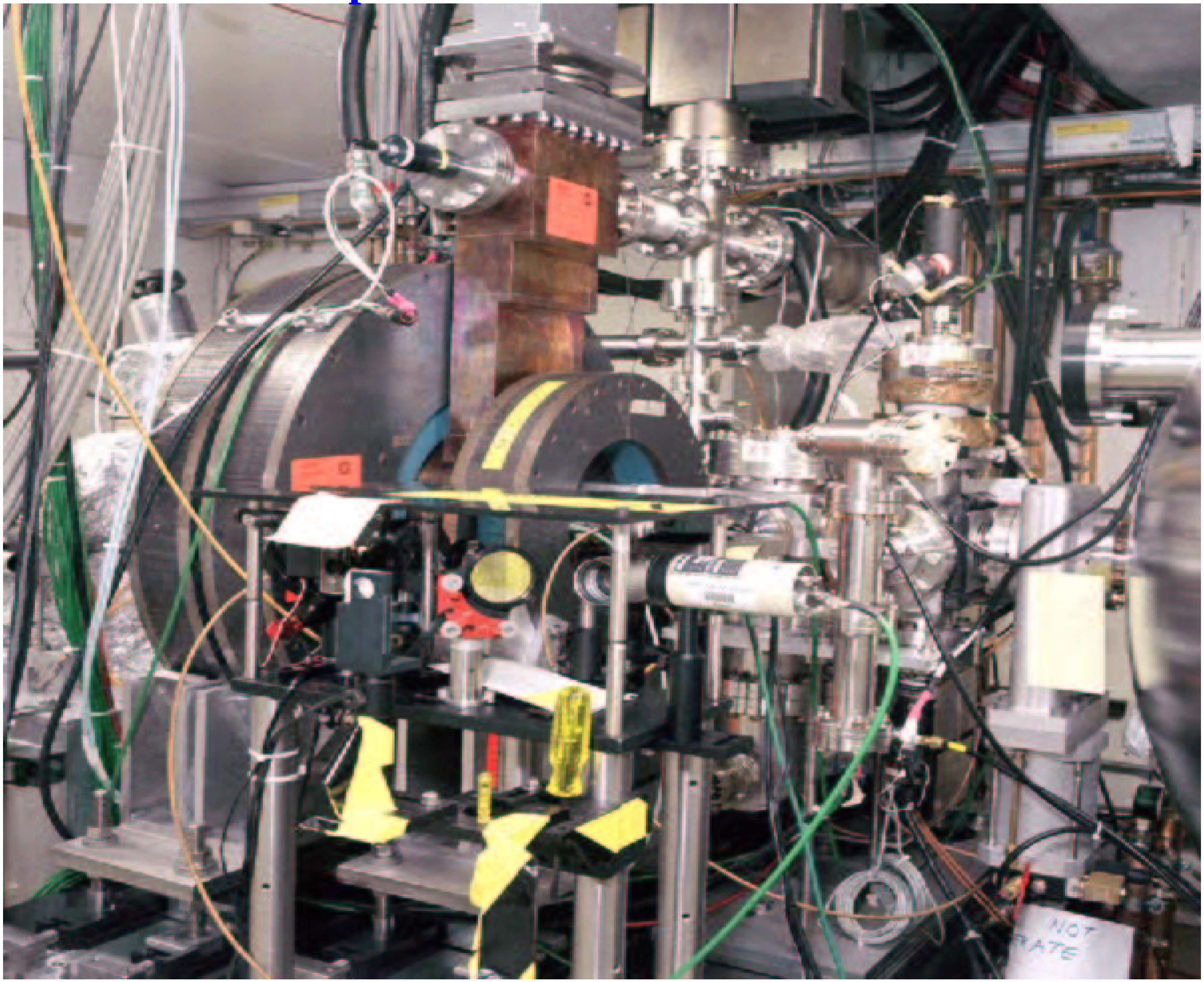


(Courtesy Y.E. Sun)



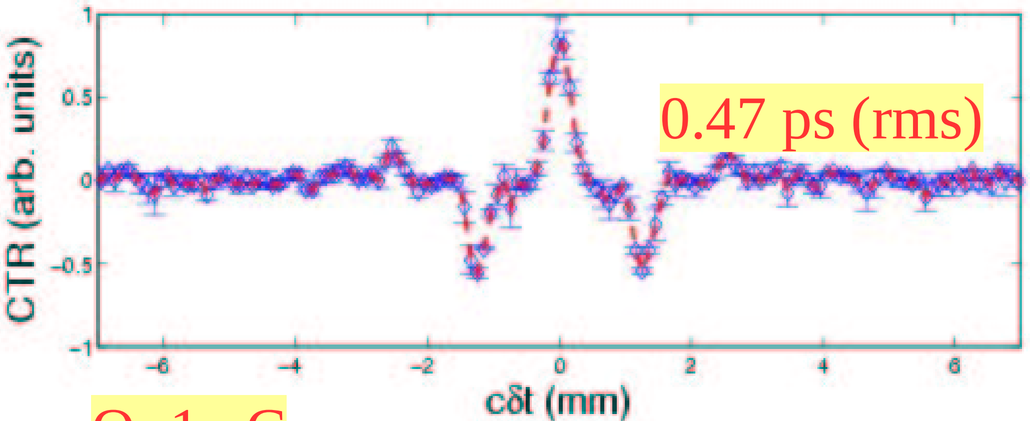
FNAL/NICADD photo-injector Laboratory

-the photo-emission electron source-

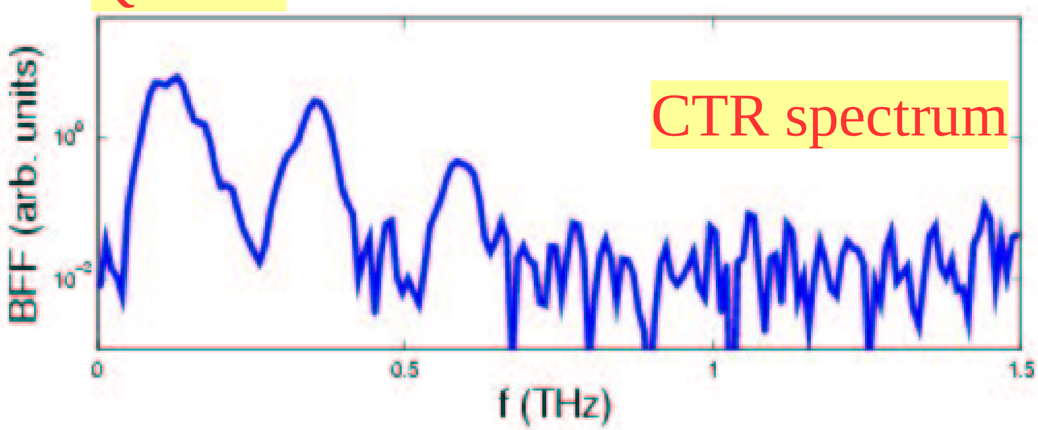


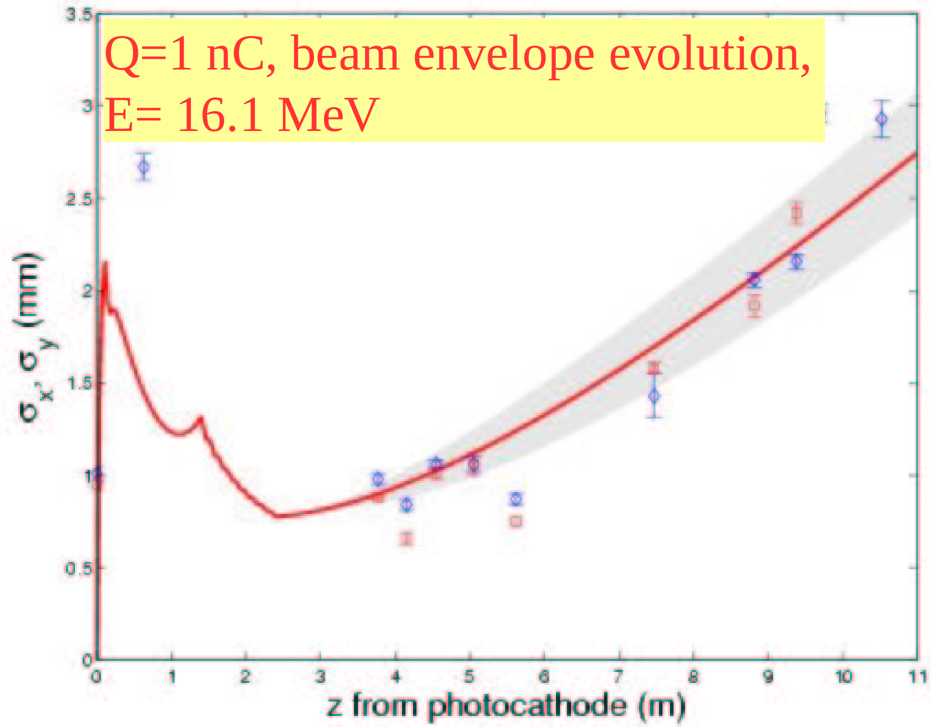
Improving model and instrumentation

- Experimental and numerical investigation of transverse and longitudinal dynamics of space-charge-dominated beams – benchmarking of different numerical models



Q=1 nC

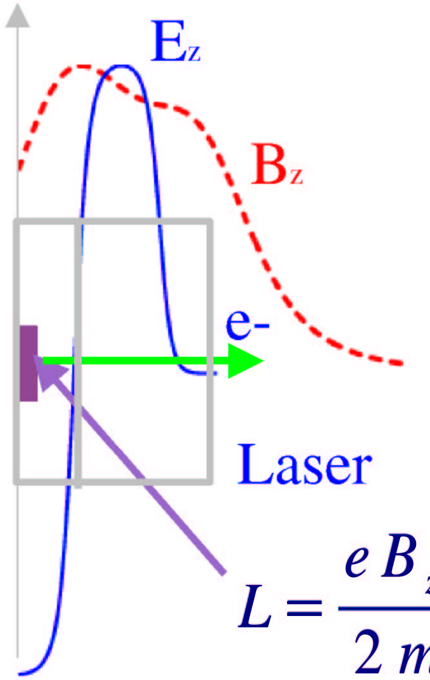




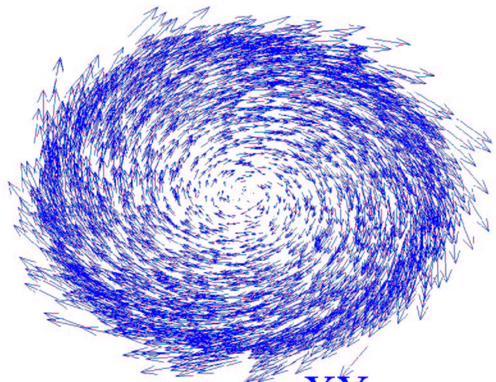
- Bunch length measurement of sub-ps e- bunch using freq-domain analysis of coherent transition radiation

[D. Mihalcea, (2003)]

Photoinjector production of flat beams



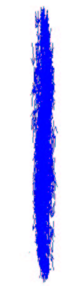
$$L = \frac{e B_z \sigma_c^2}{2 m_e c}$$



Skew quadrupole

channel

$$\varepsilon_{x,y} = [L^2 + \varepsilon_{th}^2]^{1/2} \pm L$$



[R. Brinkmann et al, PRSTAB 4, 053501 (2001)]

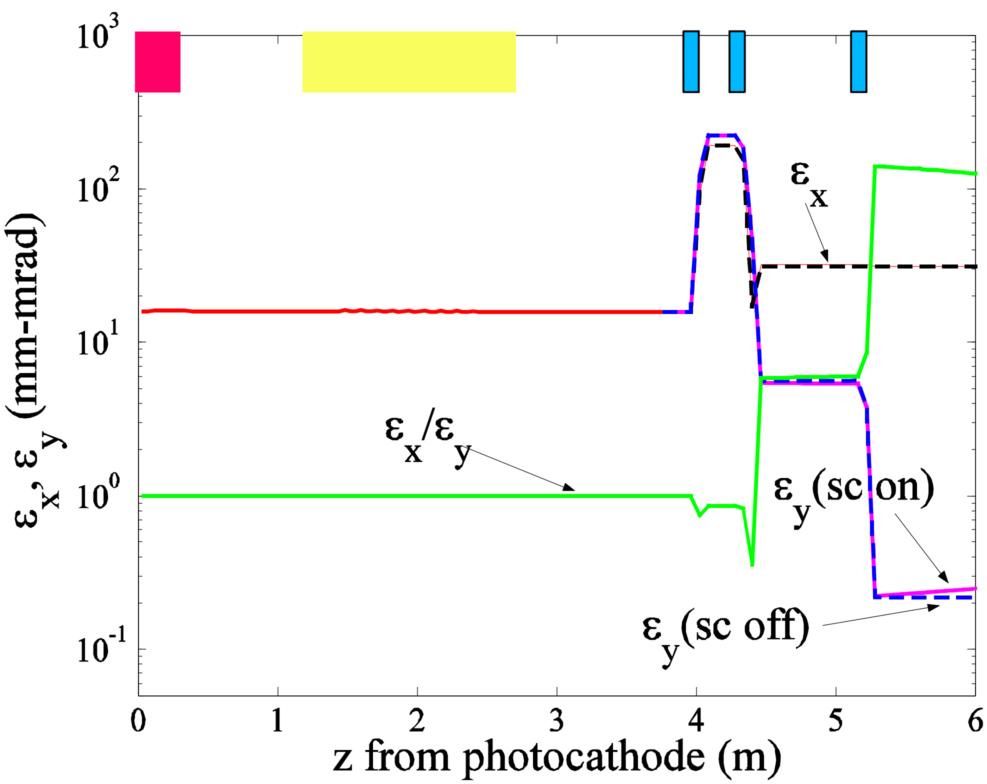
- Production of an angular-momentum-dominated e- beam ("magnetized beam")
- Outside of B-field region, (canonical) angular momentum converted into mechanical angular momentum
- Downstream, a set of properly tuned skew quadrupoles ("*Derbenev transform*") applies a net torque on the beam that cancels the mechanical angular momentum

Parameters for the flat beam experiment

parameter	value	units
laser injection phase	25 ± 5	rf-deg
laser radius on cathode	0.6-1.6 ($\pm$ 0.05)	mm
laser pulse duration	4 ($\pm$ 0.5)	ps
bunch charge	0.2-1.6	nC
E_z on cathode	$34\text{-}35 \pm 0.2$	MV/m
B_z on cathode	200-1100	Gauss
booster cavity acc. gradient	~ 12	MV/m

- Initial conditions have been varied. Typical parameter are in the Table

- Simulated performances of the present FNPL predicts emittance ratio >100 (with realistic assumption for initial conditions)
- Space charge force tends to deteriorate the smallest of the flat beam emittances
- Emittance must be measured as close as possible to the RFTB transform

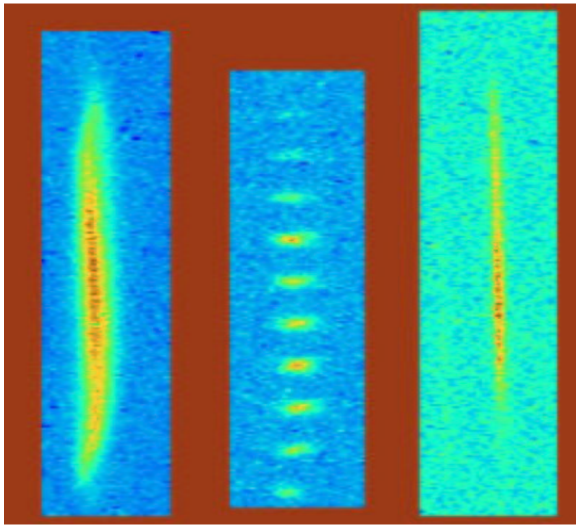


Some history…

➢1988: *Reich et al.*
partial decorrelation noted downstream of an ECR source using one skew quadrupole

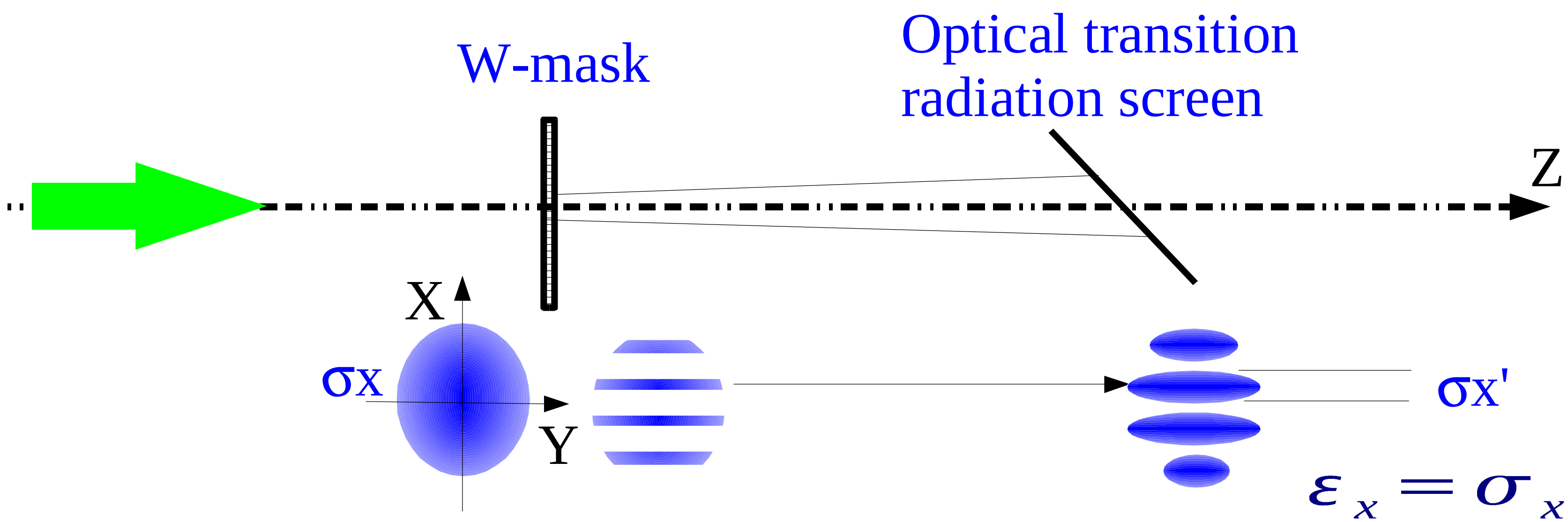
➢2000: *D. Edwards et al.*
total decorrelation and production of flat beam demonstrated at FNPL

➢On-going work:
- angular momentum-dominated beams, and on better understanding of decorrelation
- aim is to demonstrate emittance ratio>100 by end of this year



$$\frac{\varepsilon_y}{\varepsilon_x} \approx 50$$

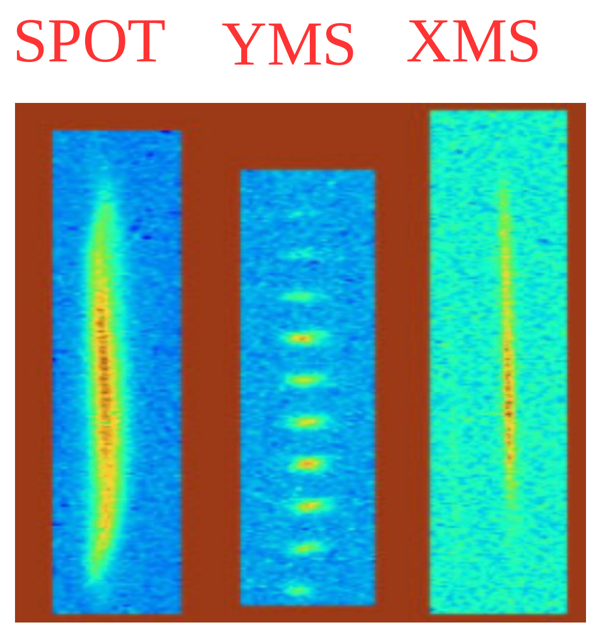
Measurements of transverse emittances



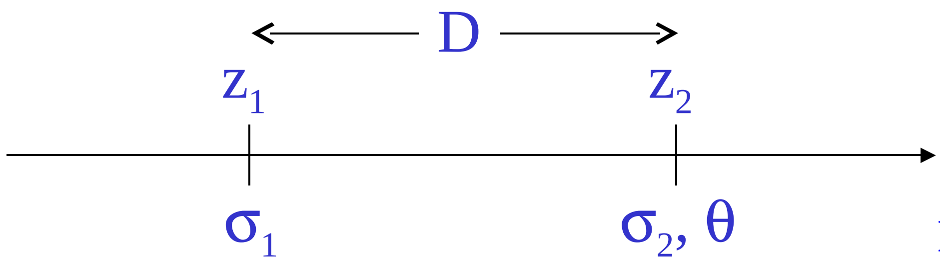
$$\varepsilon_x = \sigma_x \sigma_x'$$

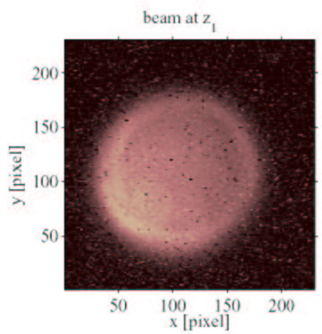
- Incoming beam is sliced by a multislit mask (W mask with 50 μm slits separated by 1mm)

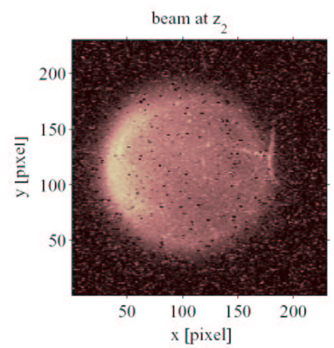
- The thereby generated beamlets are drifted up to a transverse density monitor from which the divergence is inferred

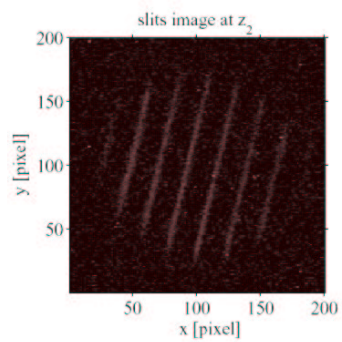


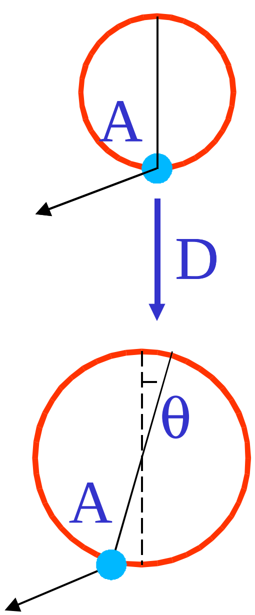
Angular-momentum measurements











- Measure beam sizes at z1 and z2
- Insert multislit-mask at z1 and measure tilt angle of the thereby generated beamlets
- The **mechanical** angular momentum is then given by:

$$\langle L \rangle = 2P_z \frac{\sigma_1 \sigma_2 \sin\theta}{D}$$

beam momentum

<u>this assumes:</u>

1/ space charge forces are not dominant in the beam evolution,

2/ the beam is laminar

Angular-momentum measurements

-varying laser spot-size on photocathode-

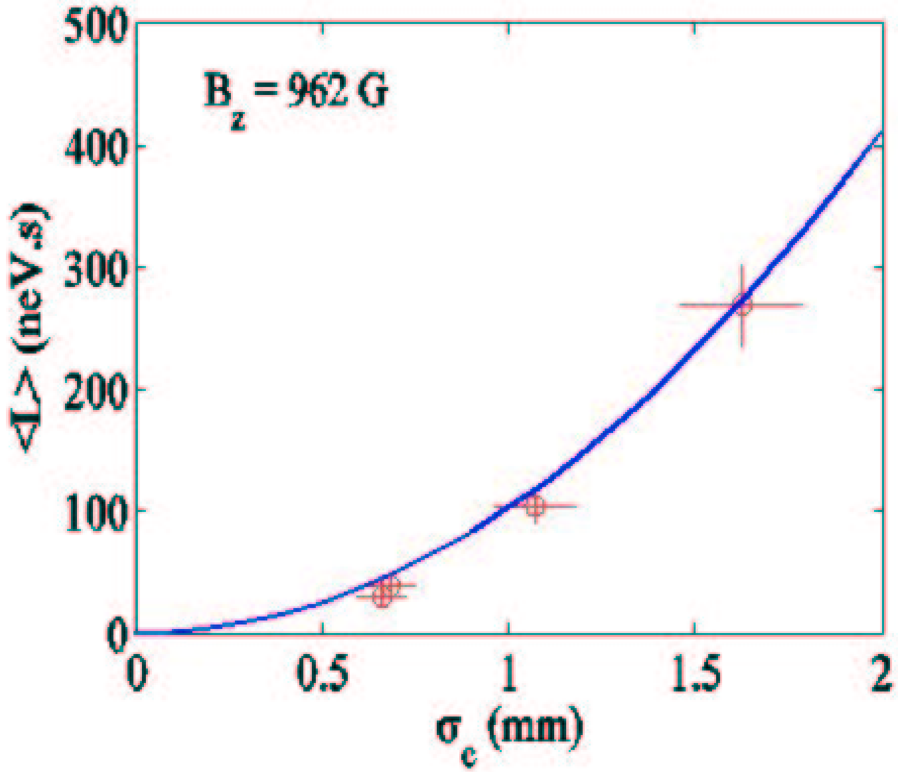
- Scaling of mechanical angular momentum on beam size on photo-cathode surface was also verified

B-field on cathode (POISSON)

$$\langle L \rangle = e B_0 \sigma_c^2$$

averaged CAM

transverse rms size on photocathode



(Y.-E Sun et al,ArXiv:physics/0411063 v1 6 Nov 2004)

Angular-momentum measurements

➢Conversion of canonical angular momentum into mechanical angular momentum is as predicted

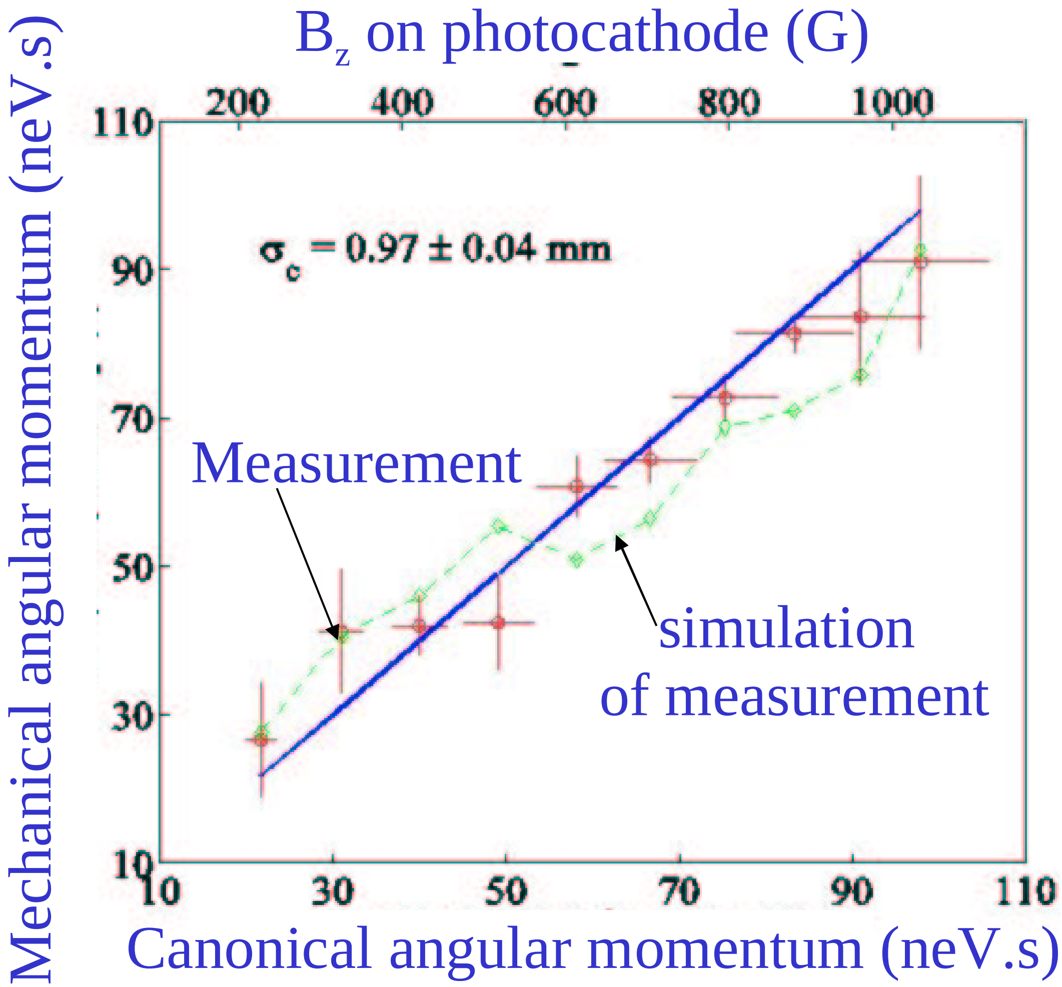
➢CAM calculated from:

B-field on cathode
(POISSON)

$$\langle L \rangle = e B_0 \sigma_c^2$$

averaged CAM

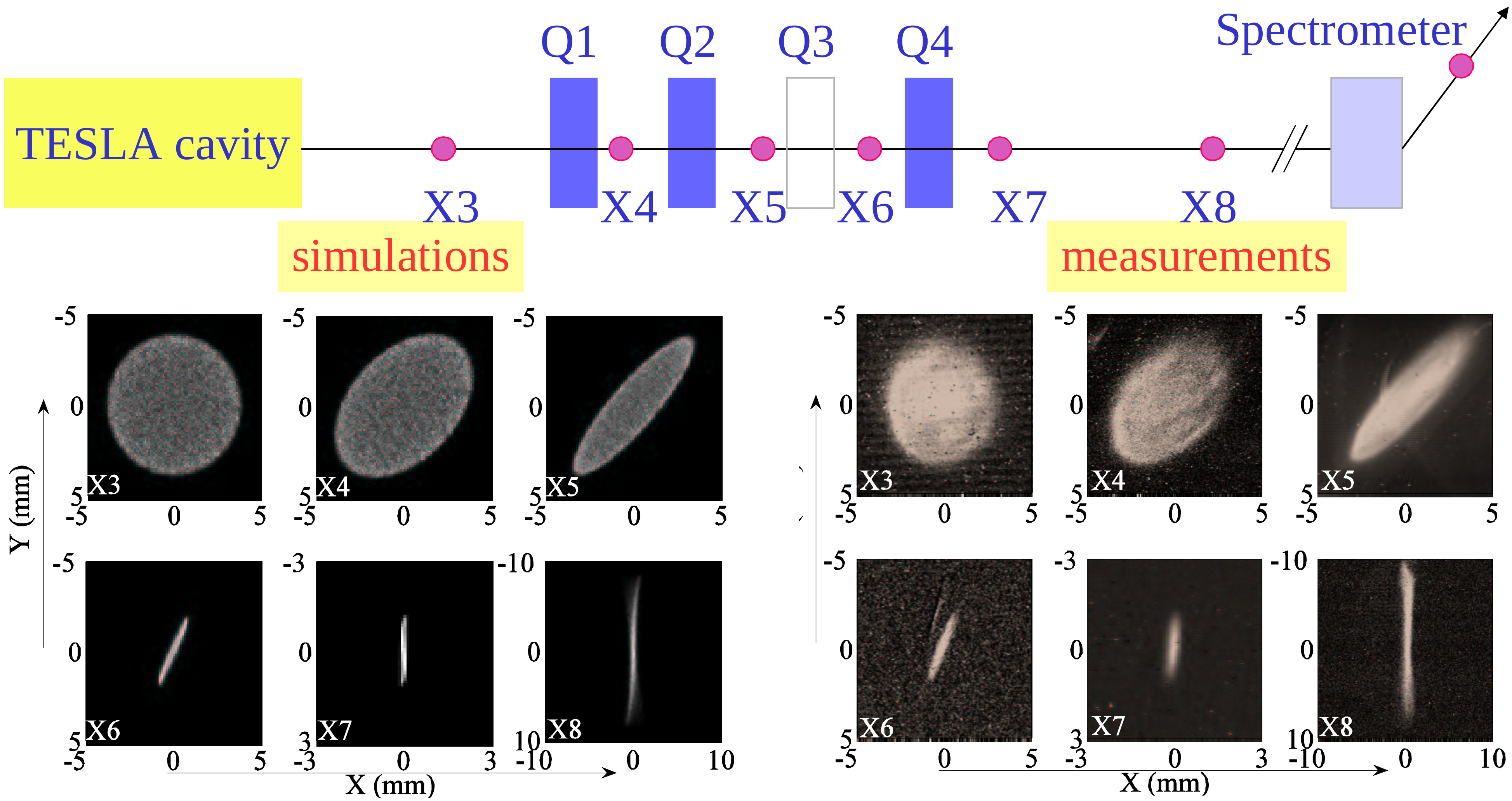
transverse rms size
on photocathode



(Y.-E Sun et al,ArXiv:physics/0411063 v1 6 Nov 2004)

Flat beam transformation

➢A skew quadrupole channel applies a torque so to cancel the incoming angular momentum. It also zeros the other term of the x-y block of the beam matrix

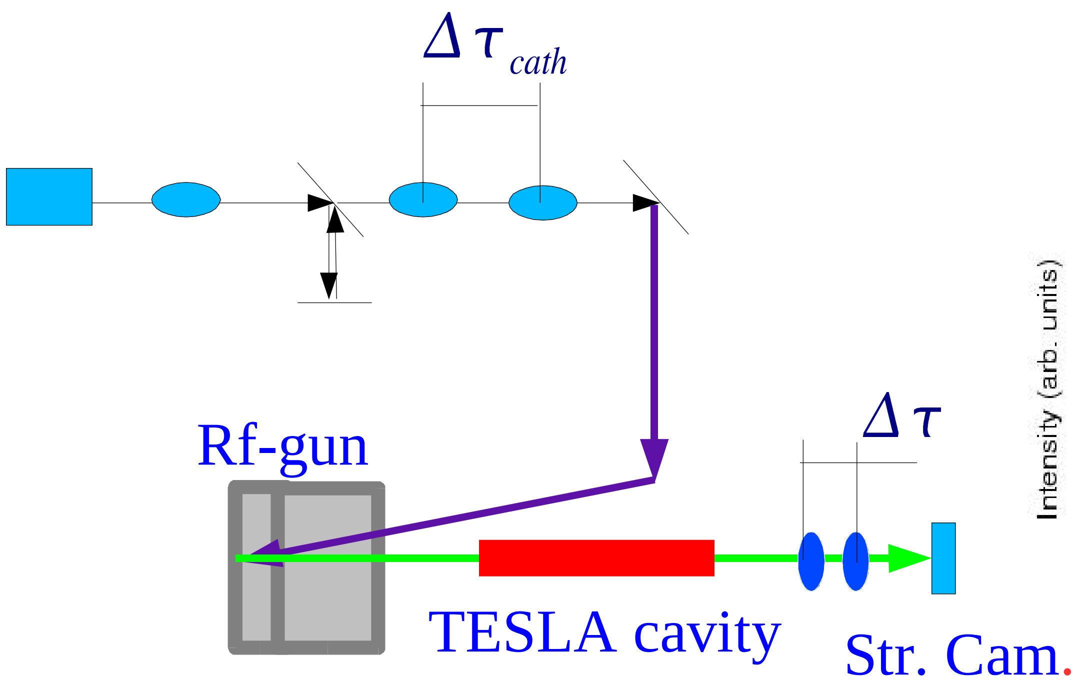


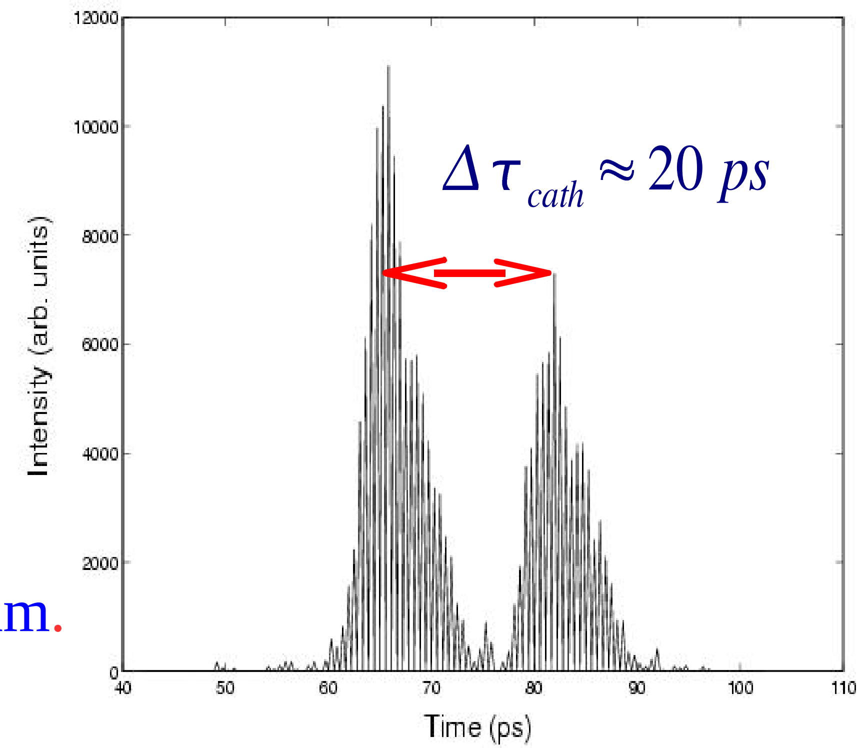
(Y.-E Sun et al,ArXiv:physics/0411063 v1 6 Nov 2004)

Two-macroparticle experiment

-single particle longitudinal dynamics investigation-

- Develop method to investigate the single particle dynamics though the linac
- Photocathode drive-laser generates two optical pulses within the same rf-bucket (thereby generating a two-macroparticles bunch)
- Measurement of relative displacement of these two macroparticles yield longitudinal focusing (=bunching) properties of the linac





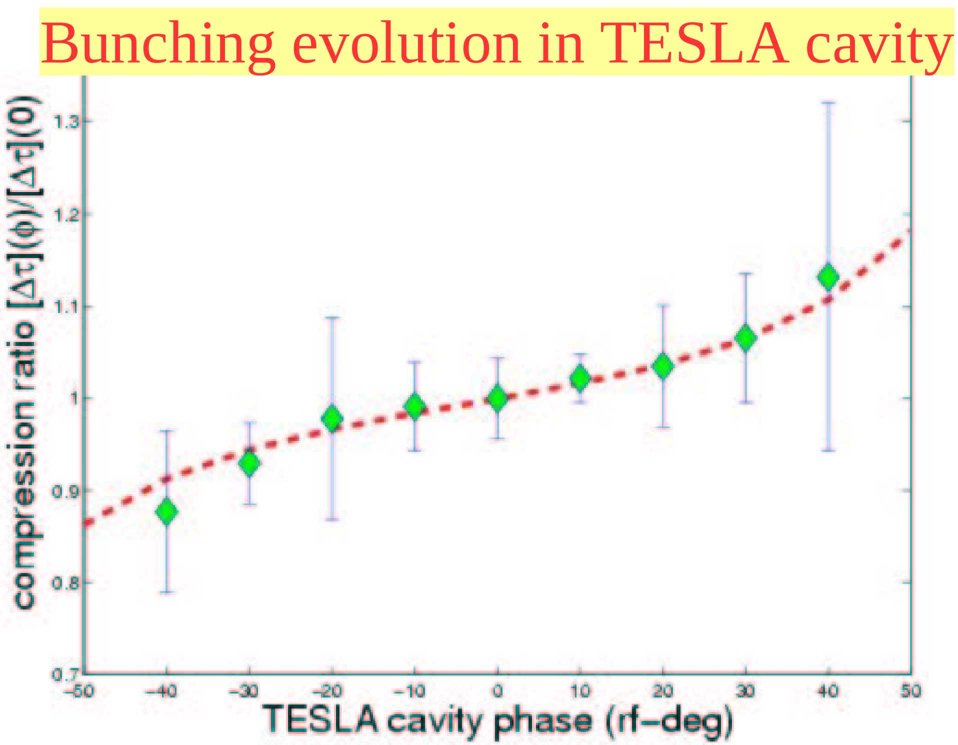
(R. Tikhoplav, proc. LINAC 2004 Luebeck)

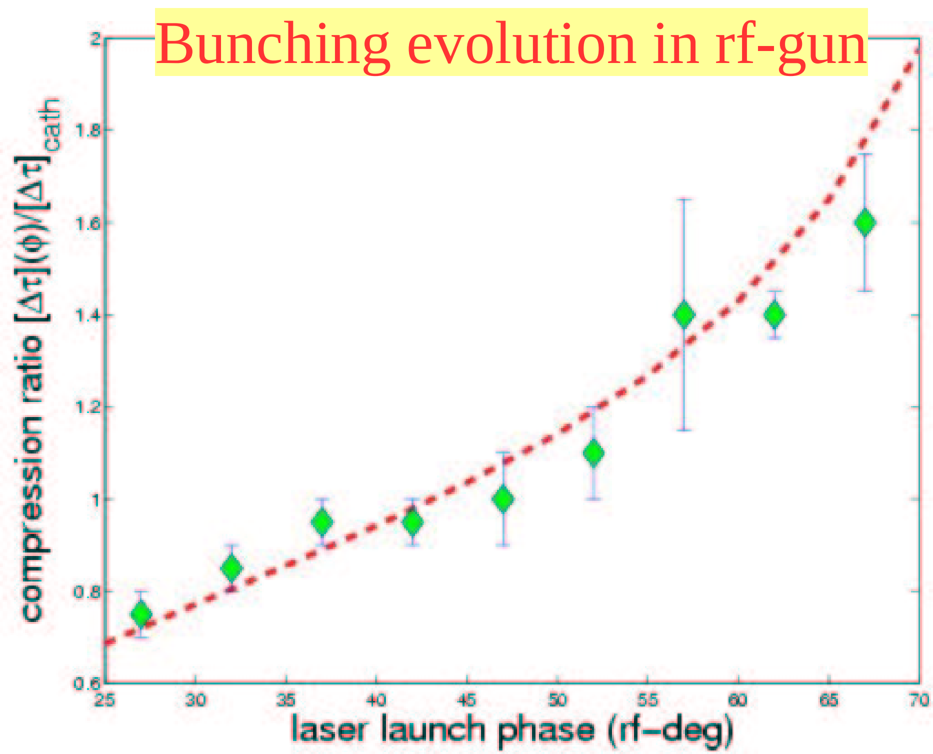
Two-macroparticle experiment

-single particle longitudinal dynamics results-

- Measured a clear focussing properties of the rf-gun and TESLA cavity as a function of injection phase of the bunch

- Also tried to characterize the magnetic compressor [not shown]



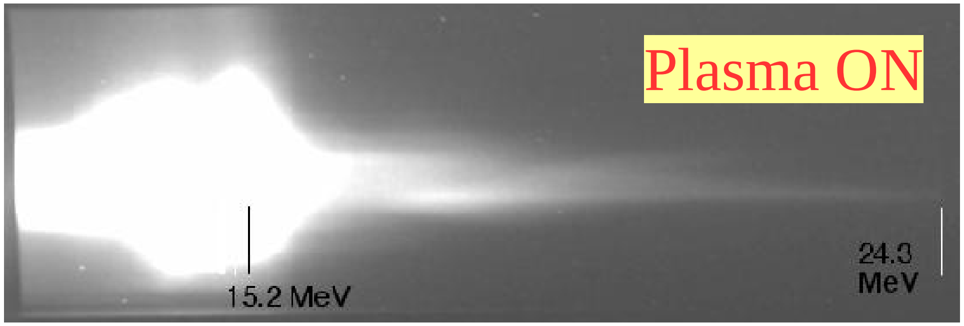


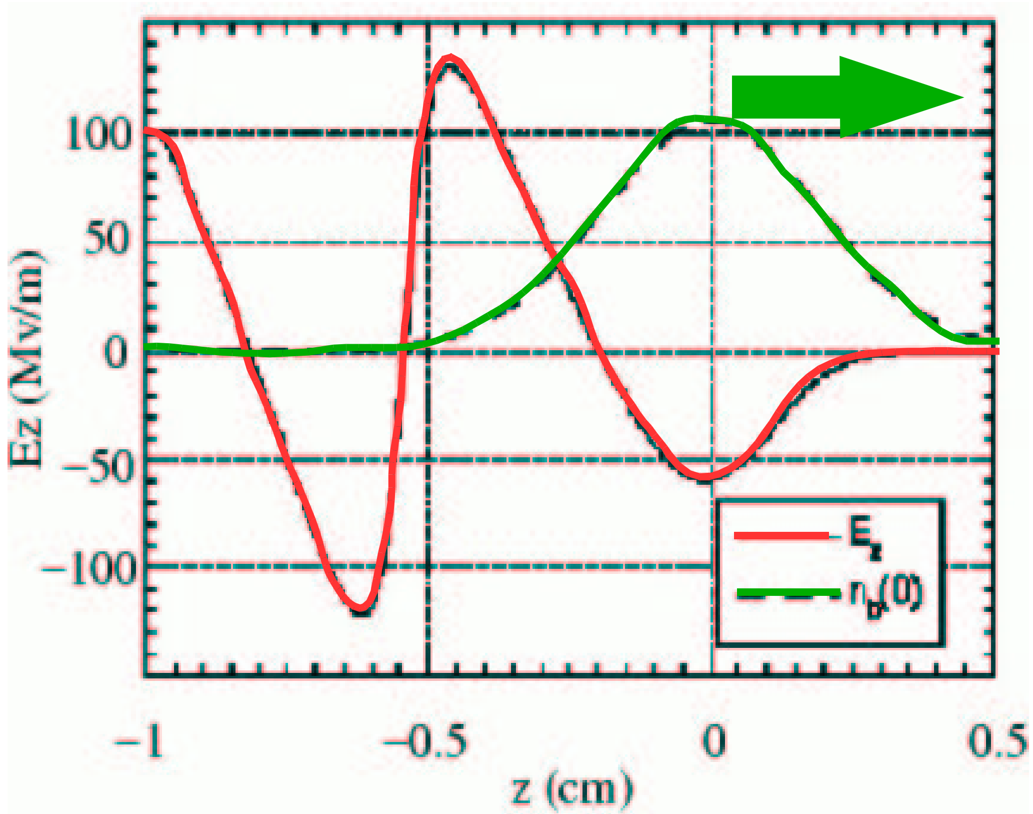
(R. Tikhoplav, proc. LINAC 2004 Luebeck)

New results on Plasma-wakefield acceleration of electrons

- High current e- beam injected in a plasma induces density modulation
- Energy in the bunch is modified according to the induced wake-field

Achieved energy gradient of 130 MeV/m





- A next set of experiments aims in sampling the plasma wake using a witness bunch following the drive beam at variable time delays

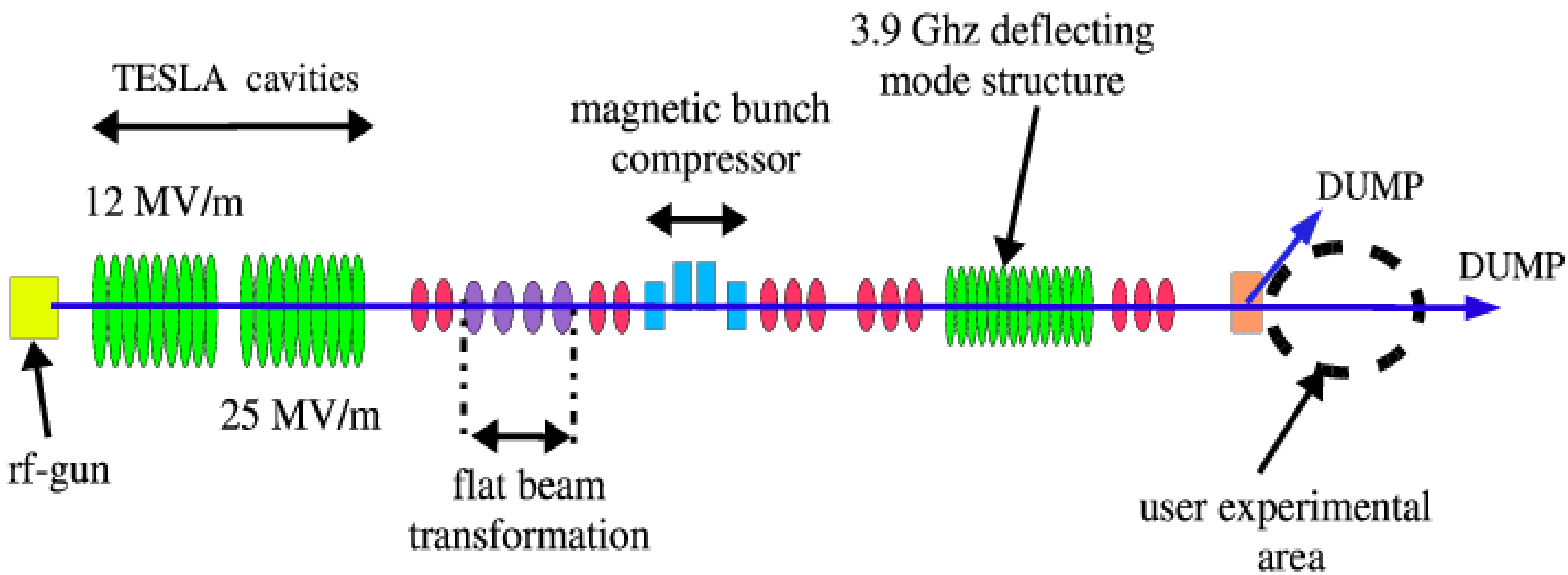
[N. Barov, submitted (2004)]

Short term energy upgrade of FNPL

- DESY has offered to give a TESLA cavity (Grad.>25 MV/m)

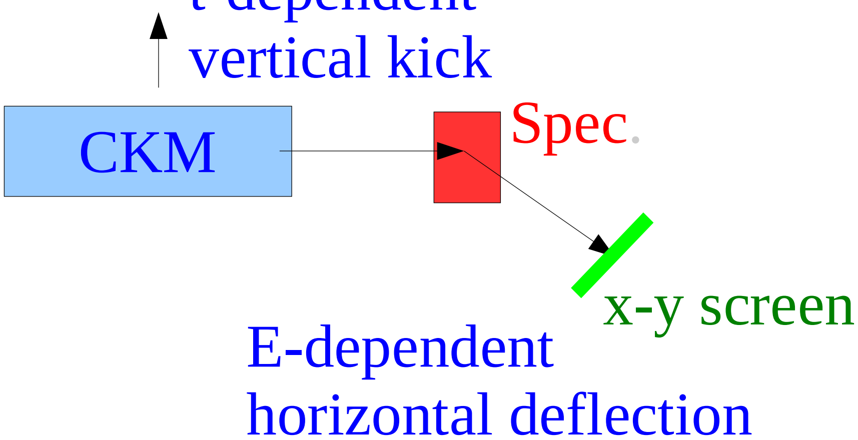
- Proposed upgrade will also eventually incorporate a 3.9 GHz dipole mode cavity being developed at FNAL in the context of CKM experiment

- Anticipated energy up to 40-50 MeV enables new regime of operation (non-space charge dominated beam)

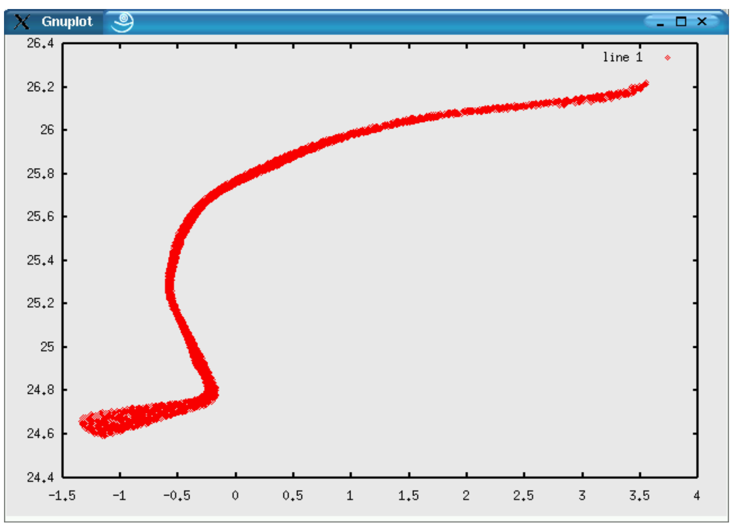


Longitudinal phase space measurement

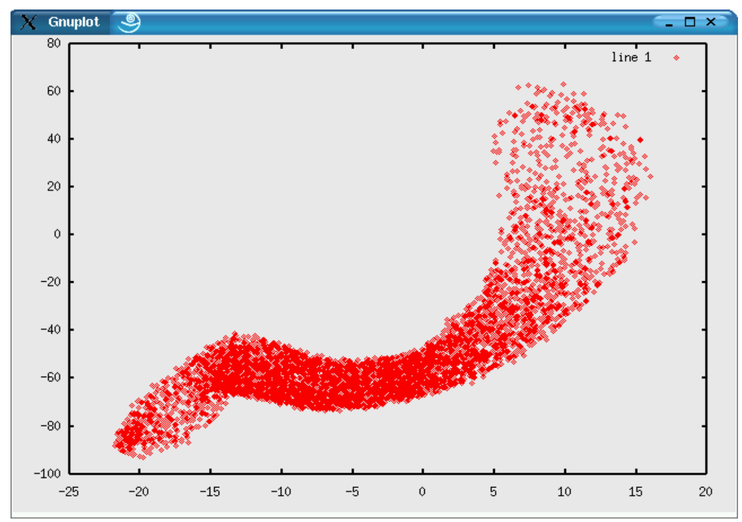
- 3.9 Ghz dipole mode cavity developed for CKM experiment in main injector



- Cavity will be tested in FNPL and will provide a unique diagnostics to study slice parameters along the bunch (e.g. ε) and reconstruct long phase space
- Cavity in conjunction with transverse collimation can be used to generate ultra-short bunches



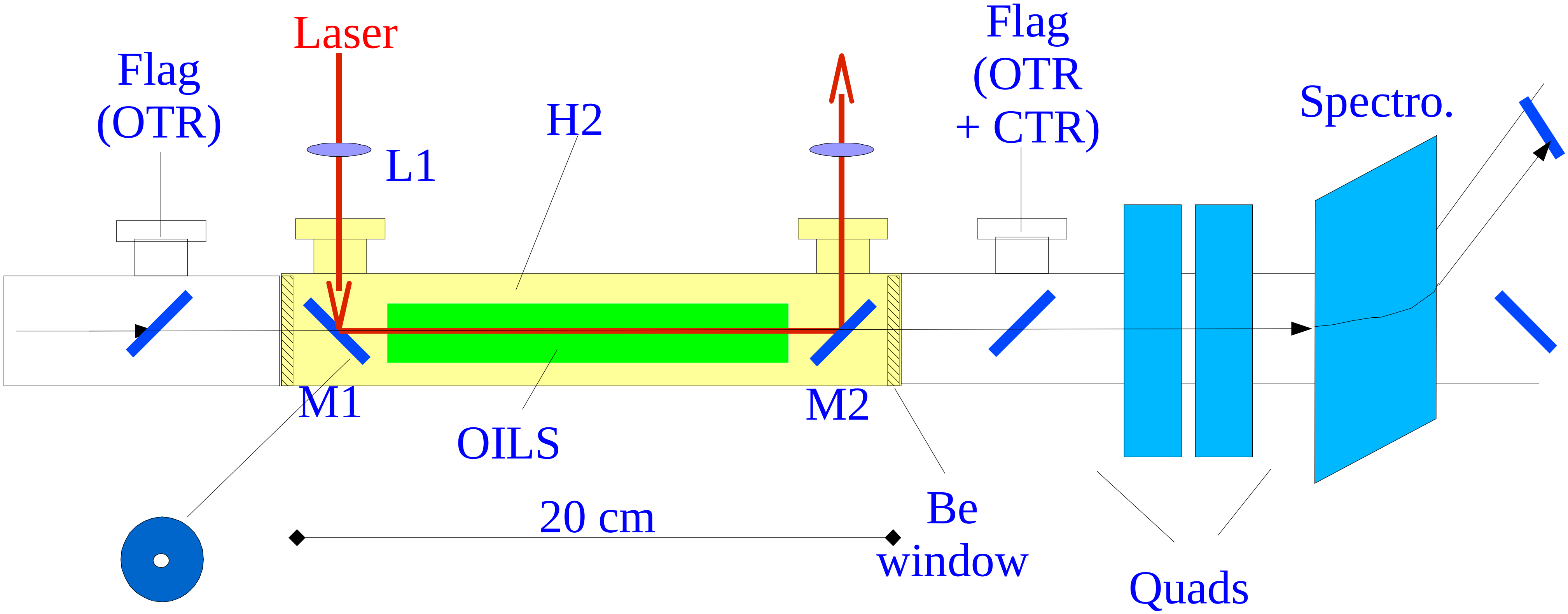
(z,δ) after bunch compressor



(x,y) at spectrometer, cavity deflecting vertically, horizontal axis is δ

Laser acceleration of electrons

- Incoming electron beam E=40-50 MeV is co-propagated with the laser in a OILS structure immersed in a pressurized H2 tank

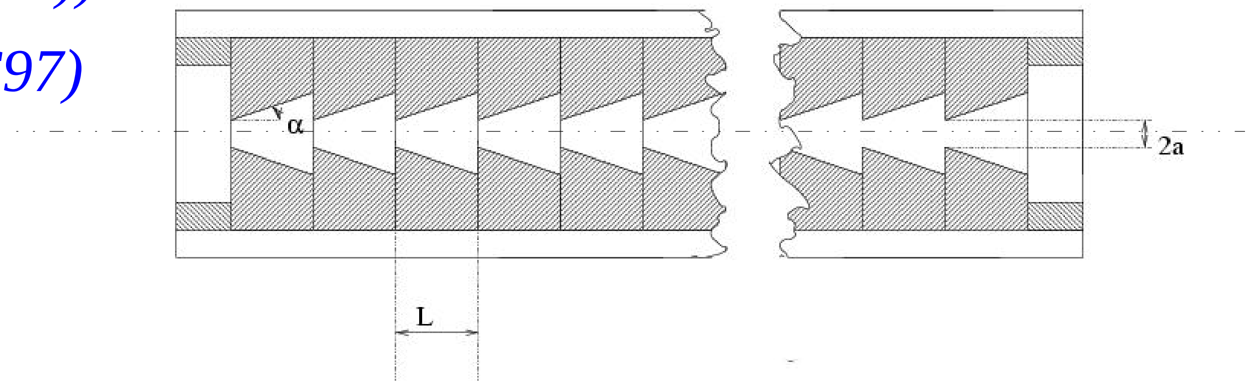


- Diagnostic to measure beam size, coherent transition radiation, + spectrometer for momentum/momentum spread measurement

The Open Iris-loaded structure

R. Pantell (NIM A 393 1-5 (1997))

M. Xie (LBNL-40558 and PAC97)



- The fields associated to TM_{01} eigenmode are given by:

$$E_z(r,z,t)=\hat{E}J_0(k_r r)\exp(i(k_z z-\omega t))$$

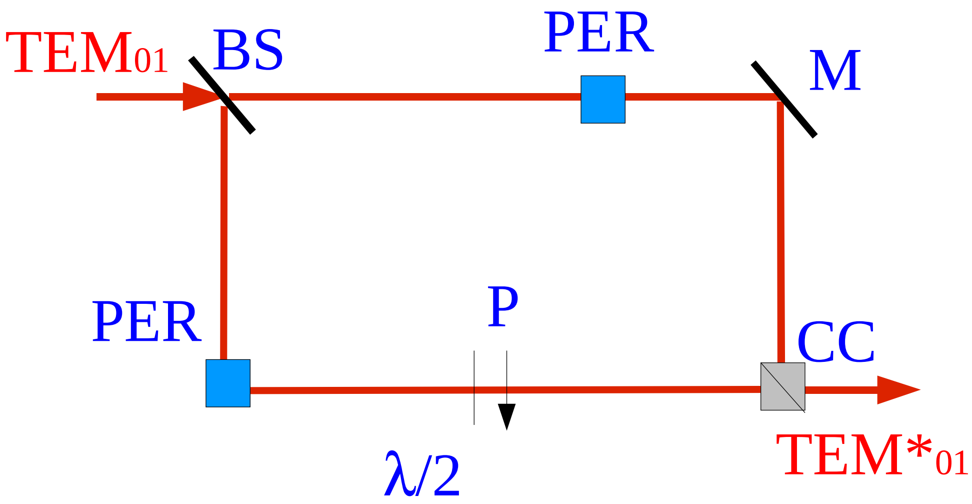
$$E_r(r,z,t)=Z_{TM}H_\phi=-i\frac{k_z}{k}\hat{E}J_1(k_r r)\exp(i(k_z z-\omega t))$$

- The phase velocity of the wave is:

$$v_\phi=\frac{\omega}{\Re(k_z)}\approx\frac{c}{n}[1+\frac{1}{2}(\frac{p_{10}\lambda}{2\pi a})]$$

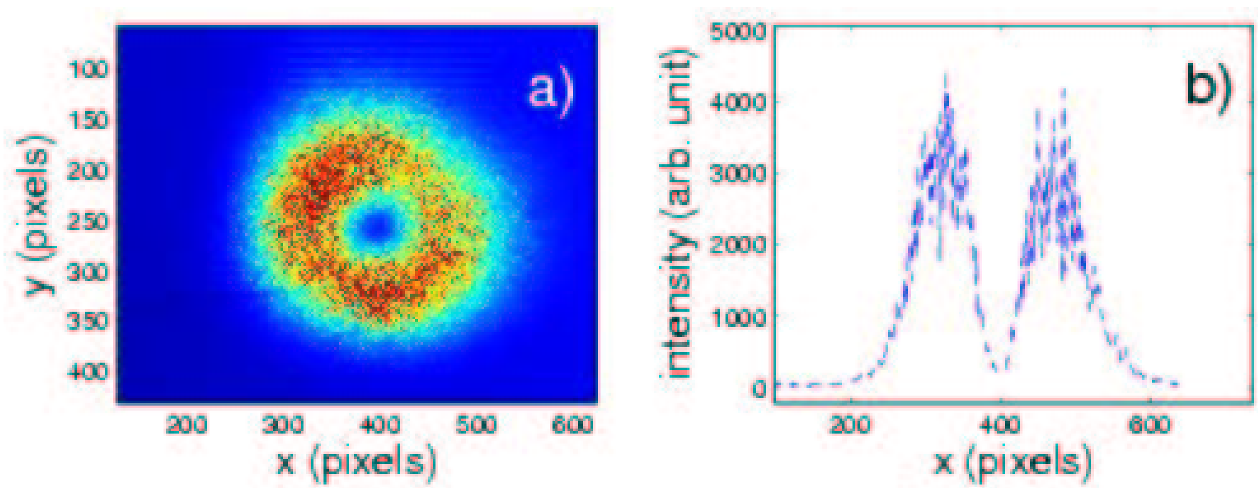
Wherein λ: wavelength, $J_1(p_{10})=0$, *n* refractive index, *c* velocity of light

Generation of "donuts" mode



-The TEM01 mode is generated by a regen. Nd:glass laser seeded by the oscillator of the photocathode drive laser

- The TEM*01 is then obtained using a Mach-Zender interferometer

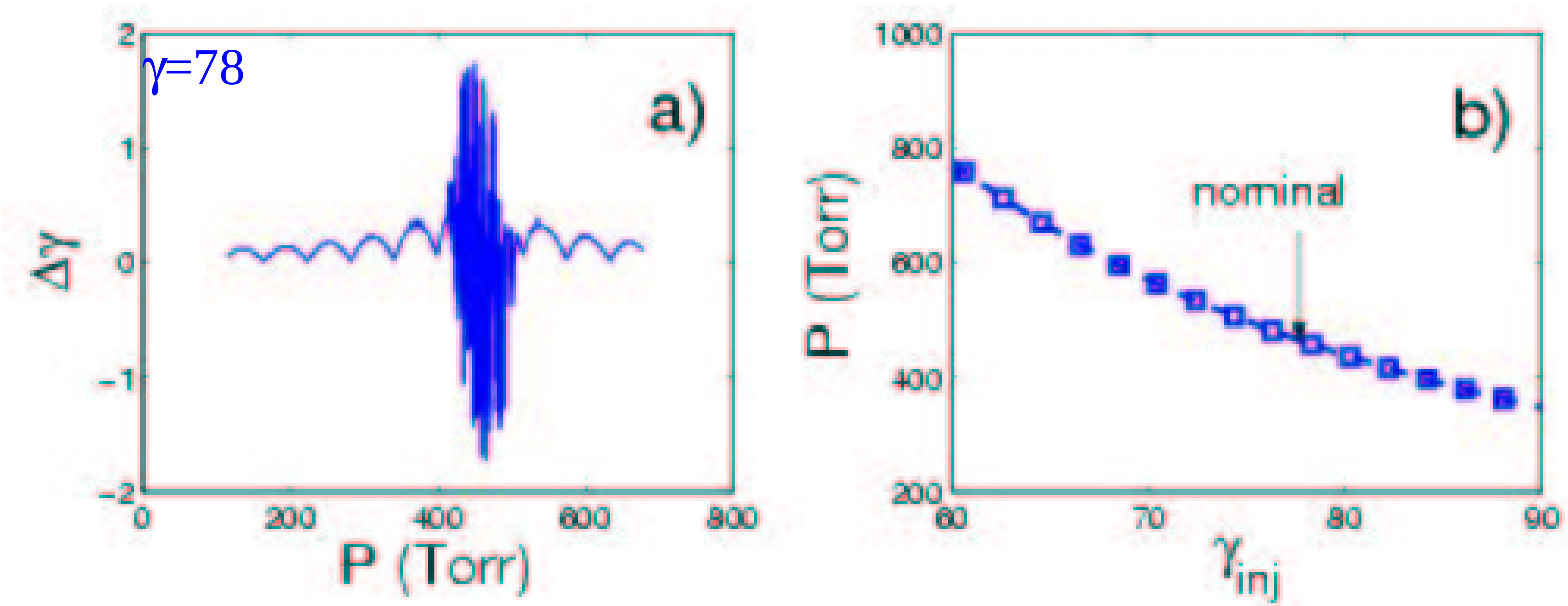


R. Tikhoplav et al. EPAC2002 984-985 (2002)

Phase matching issues

-For a nominal injection energy of 40 MeV (γ=78) we need n-1=0.000083 which corresponds to 450 Torr of H2 gas at 273.15 K

- higher injection energy will require lower pressure

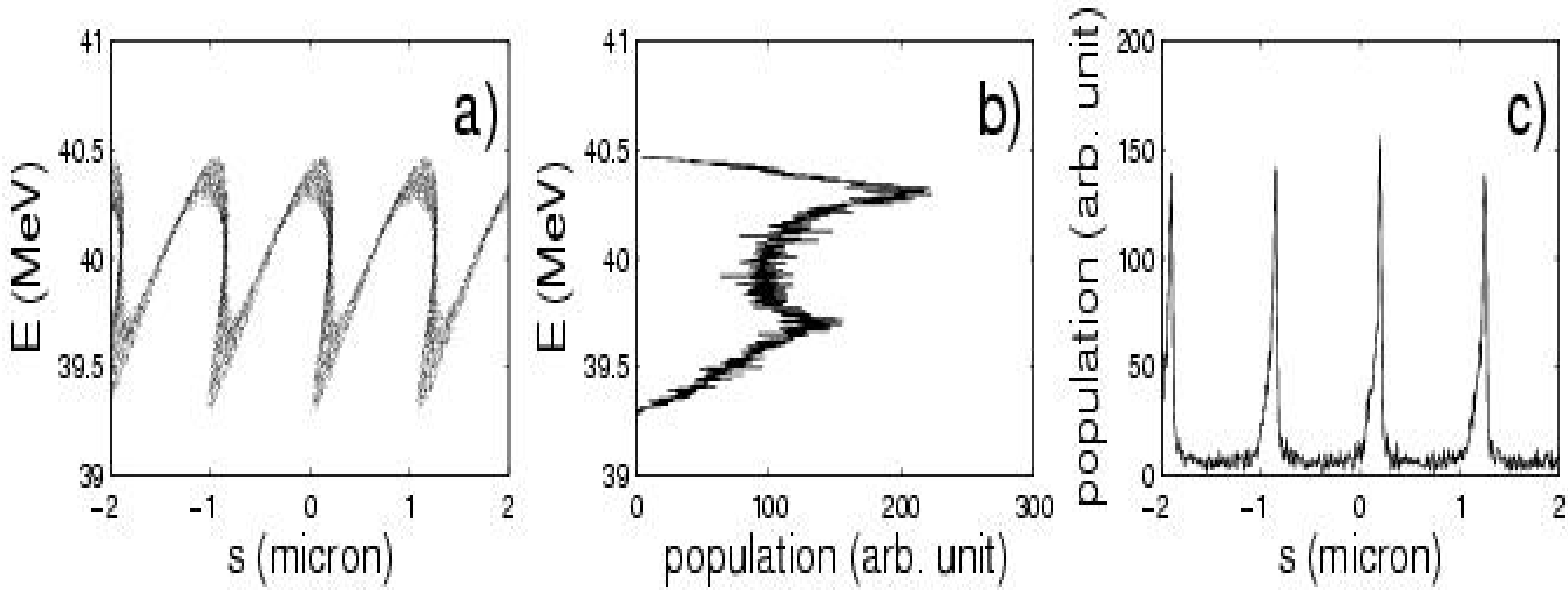


Microbunching

Given the momentum spread correlation, after a length L obeying:

$$\frac{1}{\gamma}\frac{d\,\Delta\,\gamma}{d\,\gamma} \approx \frac{-\gamma^2}{L}$$

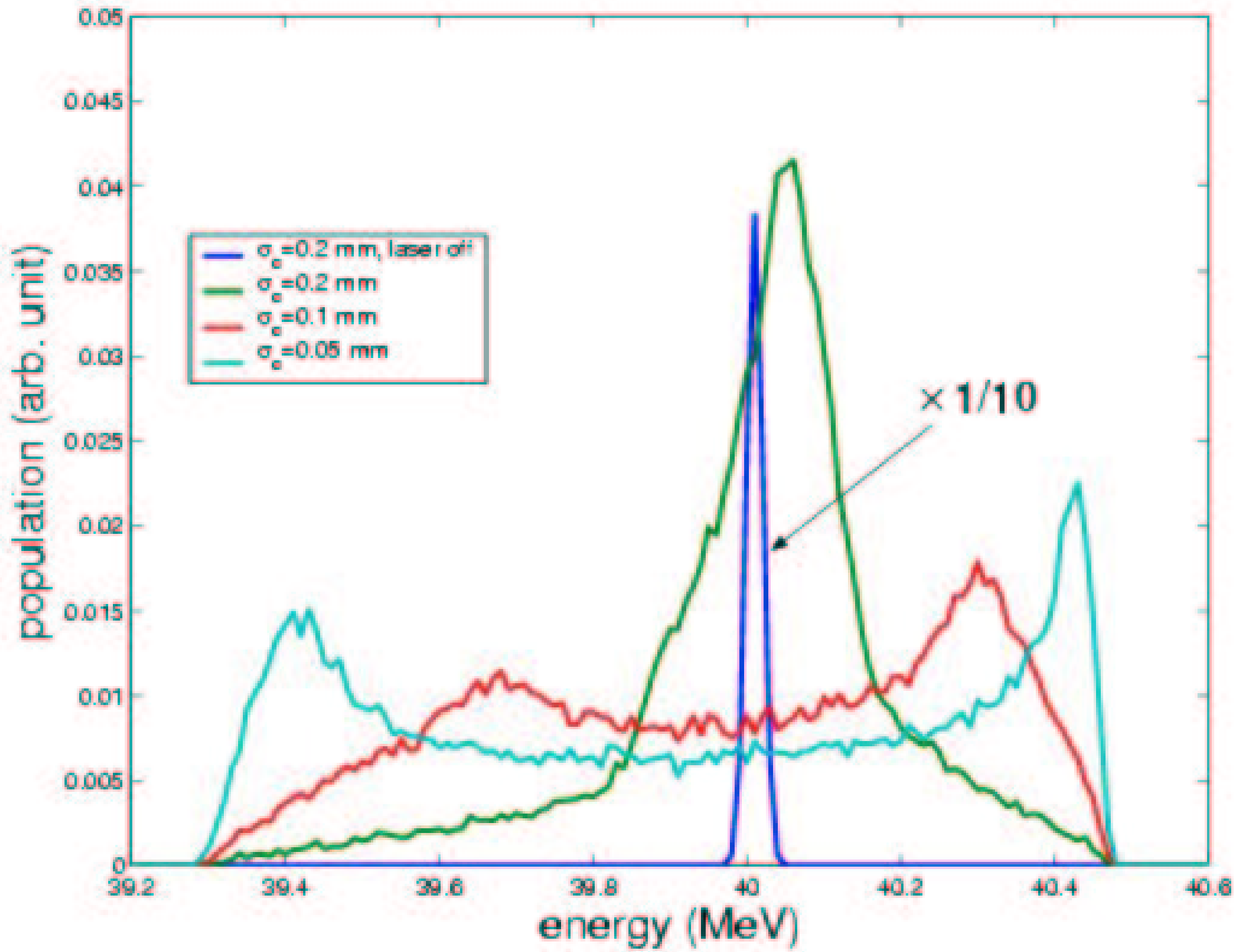
the phase space will locally be compressed, this would results in micro-bunching (density modulation of the bunch)



Longitudinal phase space and projections10 cm downstream of the OILS structure

Energy spectrum

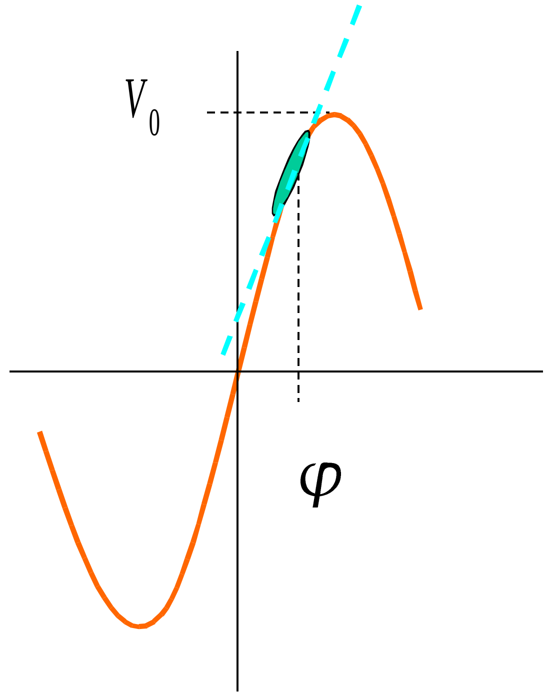
Evolution of the energy spectrum for various beam size propagating in the laser field



Toward compressed flat beams

- Induce correlated energy spread (chirp) with the accelerating cavity

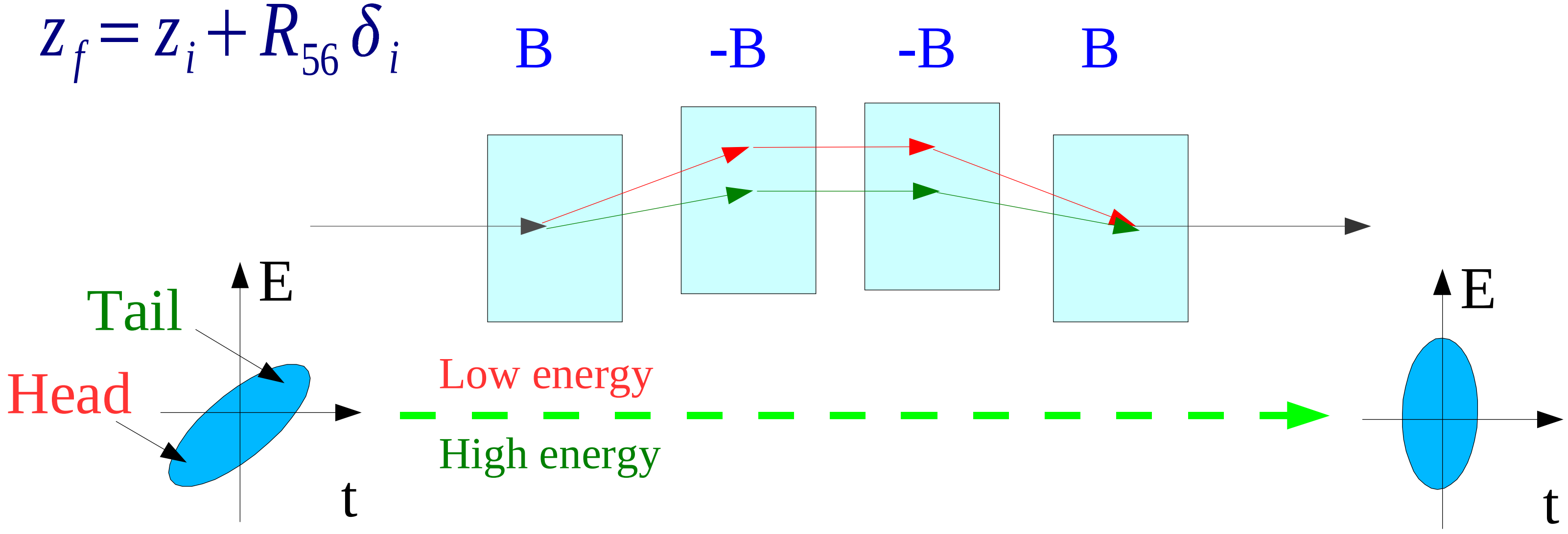
- Upstream isochronous section (chicane) compresses the bunch by introducing an energy dependent path length



$$E_z(z) = E_0 + e\,V_0 \cos(kz + \varphi)$$

1st order momentum compaction

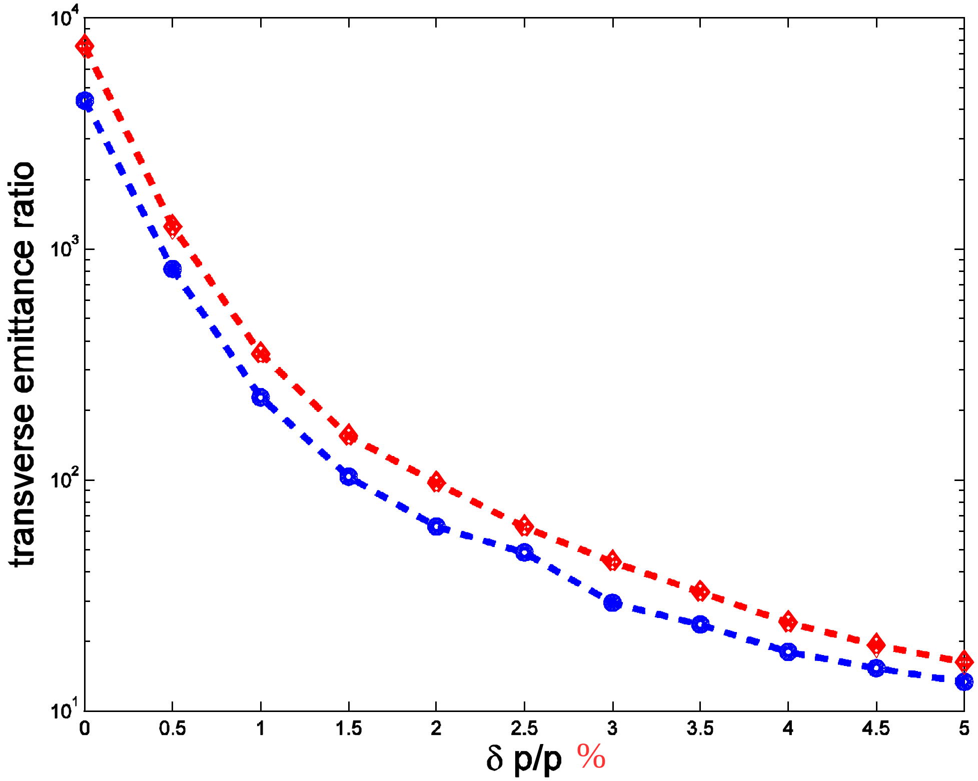
$$z_f = z_i + R_{56}\,\delta_i$$



Toward compressed flat beams

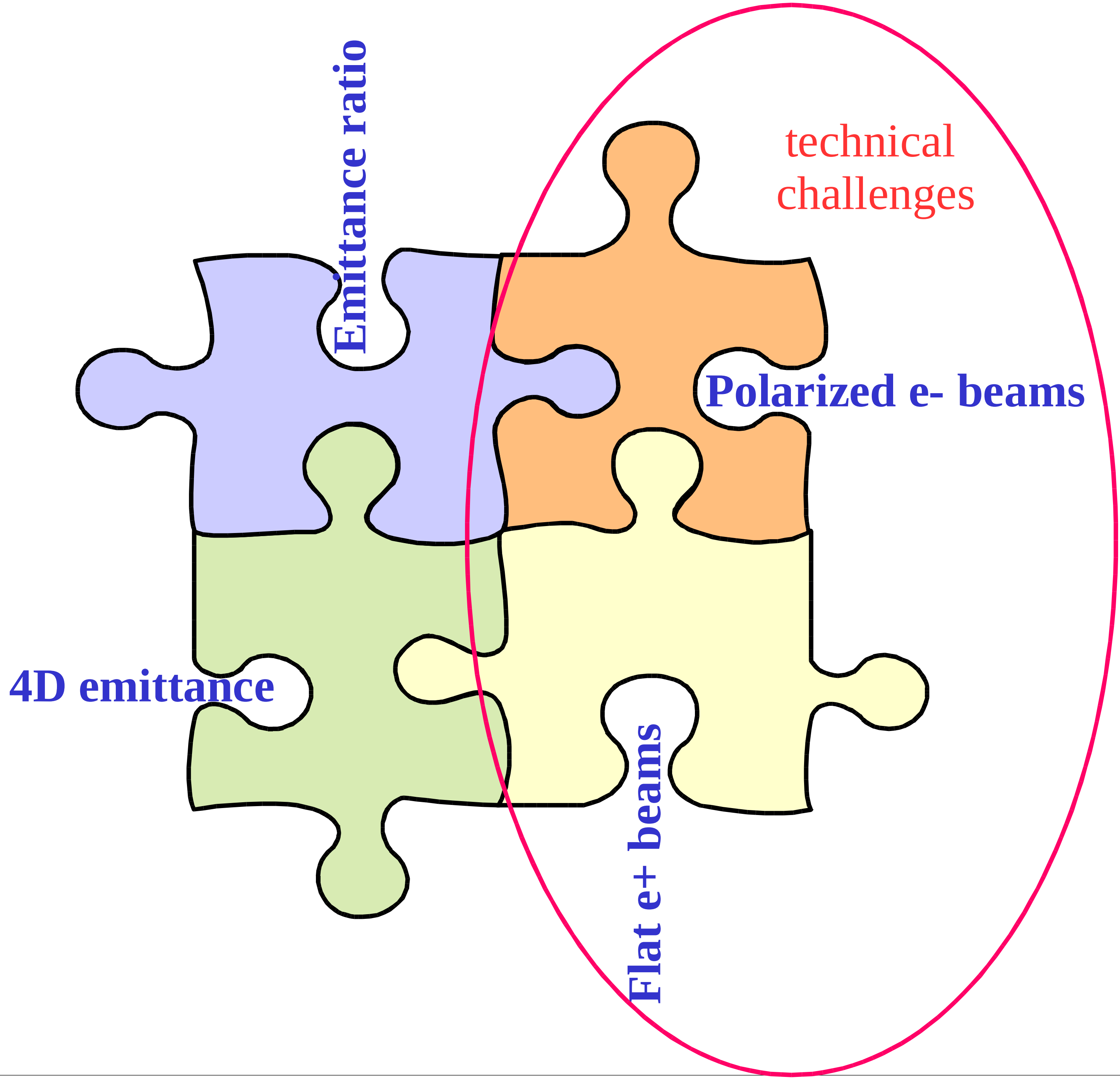
- FNPL currently incorporate a 4-bends chicane with momentum compaction of approximately -8 cm (bending angle is ~ 22.5 deg)
- The required correlated energy spread is

$$0.015 \leqslant \frac{d\,\delta}{z} \leqslant 0.1$$

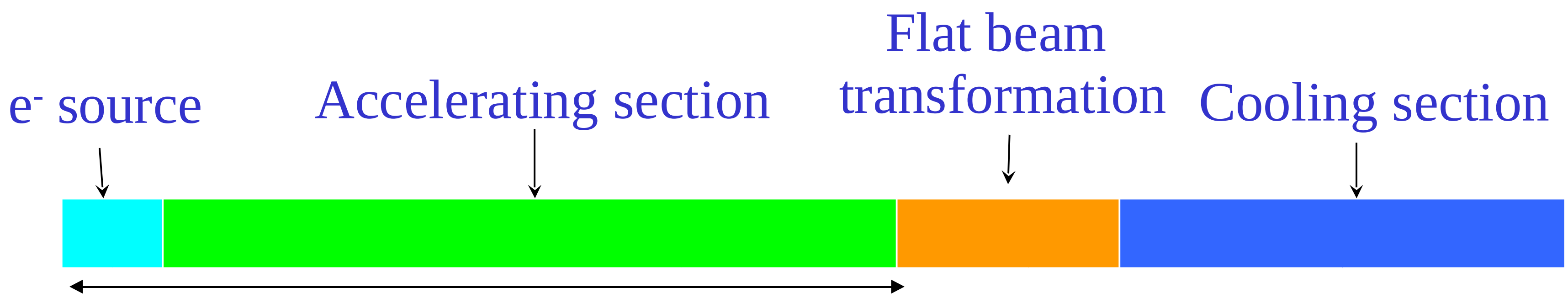


- To allow compression of flat beam, the compressor should be elongated to reduce its $|R_{56}|$.

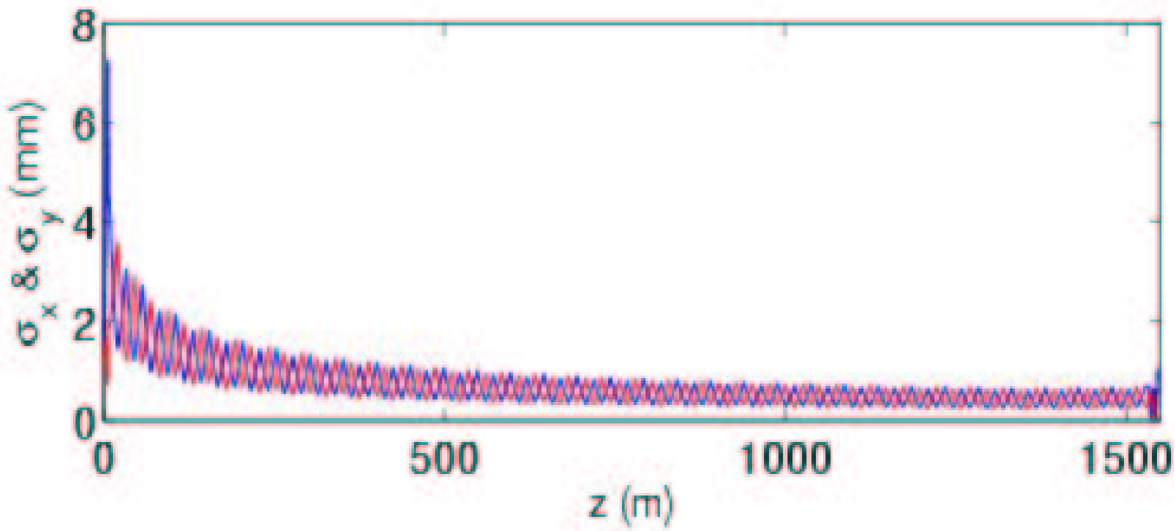
Roadmap toward removal of damping ring



A Generic flat beam injector

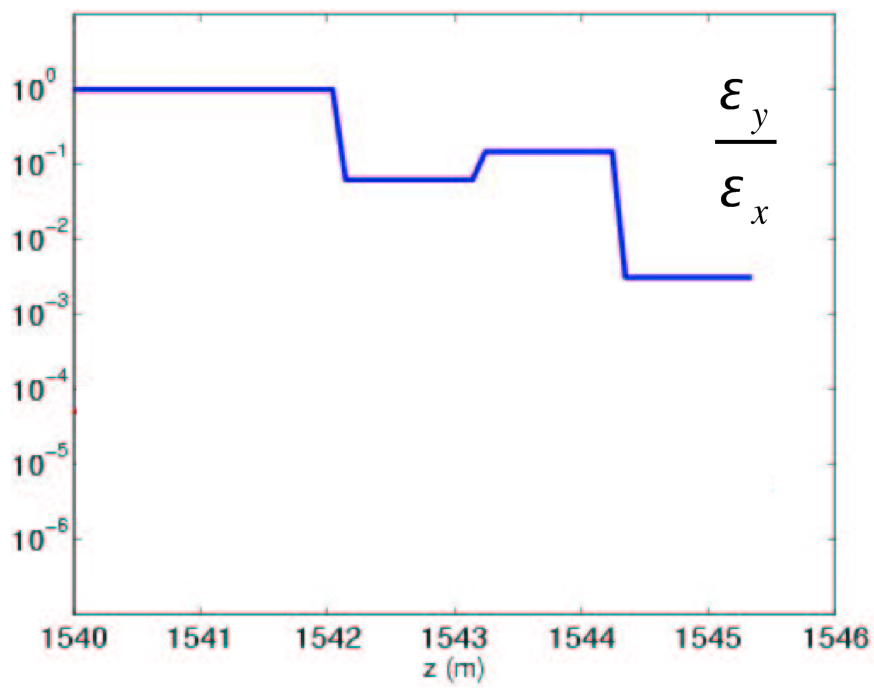


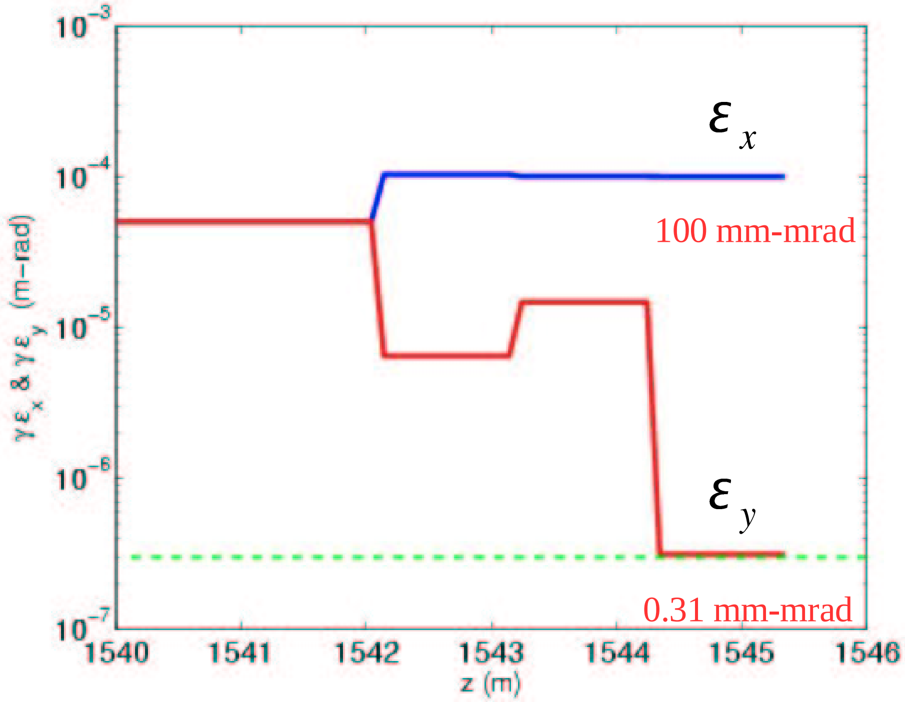
Optimized to minimize ε_{4D} while transporting an angu- -lar momentum dominated beam



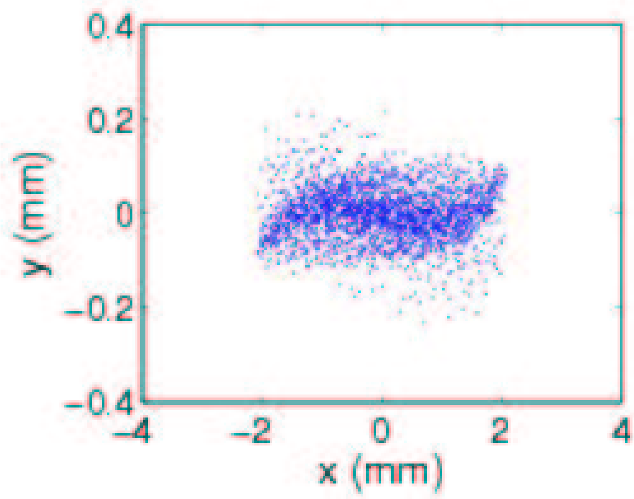
- Generate e- beam with proper angular momentum
- Transport such an angular momentum dominated beam up to high energy (e.g. 5 GeV) while conserving angular momentum
- Transform the beam into a flat beam
- Possibly cool the beam with a "moderate" cooling technique (Compton scattering scheme, or simple damping ring?)

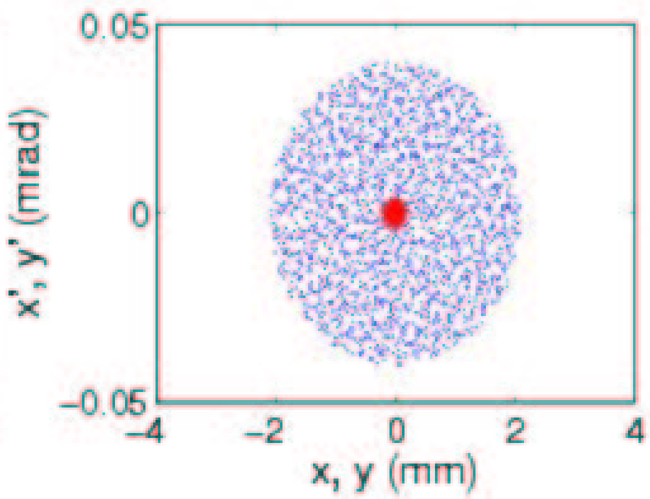
Example of preliminary optimizations of a 5 GeV injector





- Emittance ratio at 5 GeV is 320
- $\gamma\varepsilon_{4D} \approx 6\, mm\ mrad$
- Both transverse emittances are ~10 times larger than specs



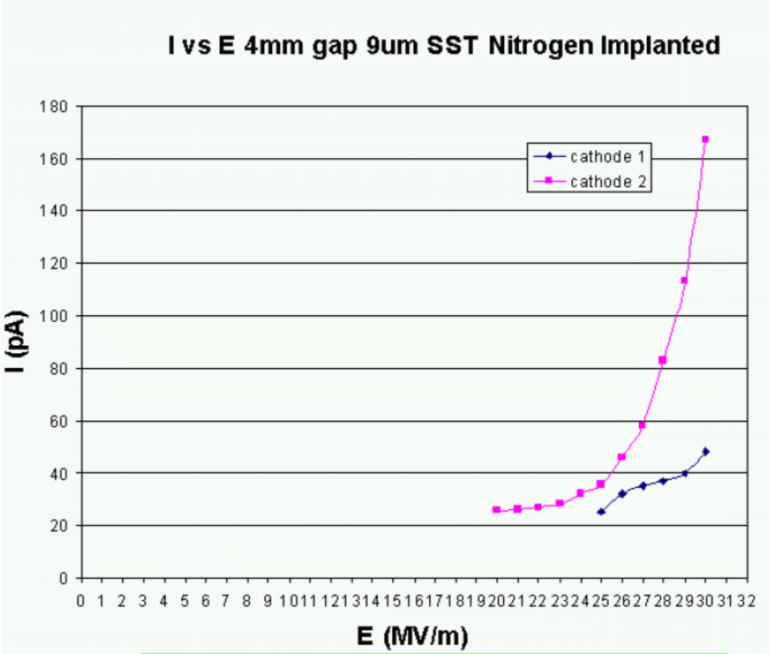


Polarized electron bunch

-challenge in operating GaAs cathode-

➢Polarized beam are traditionally obtained from GaAs Cs-doped cathode require high quality vacuum ~10^{-12} tor

➢Up to now this material as only been operated in DC gun with modest field on cathode 5 MV/m, resulting in medium quality beam and complicated injector

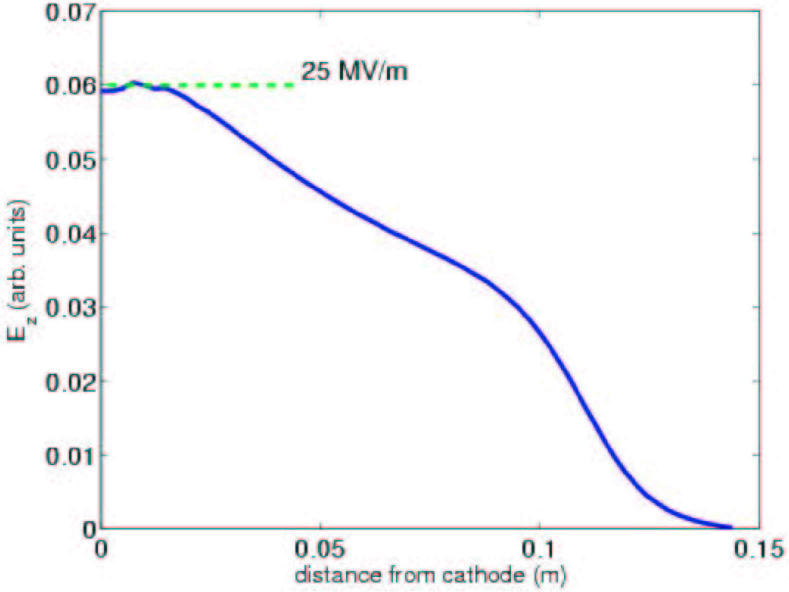


(C. Sinclair, PAC 2001)

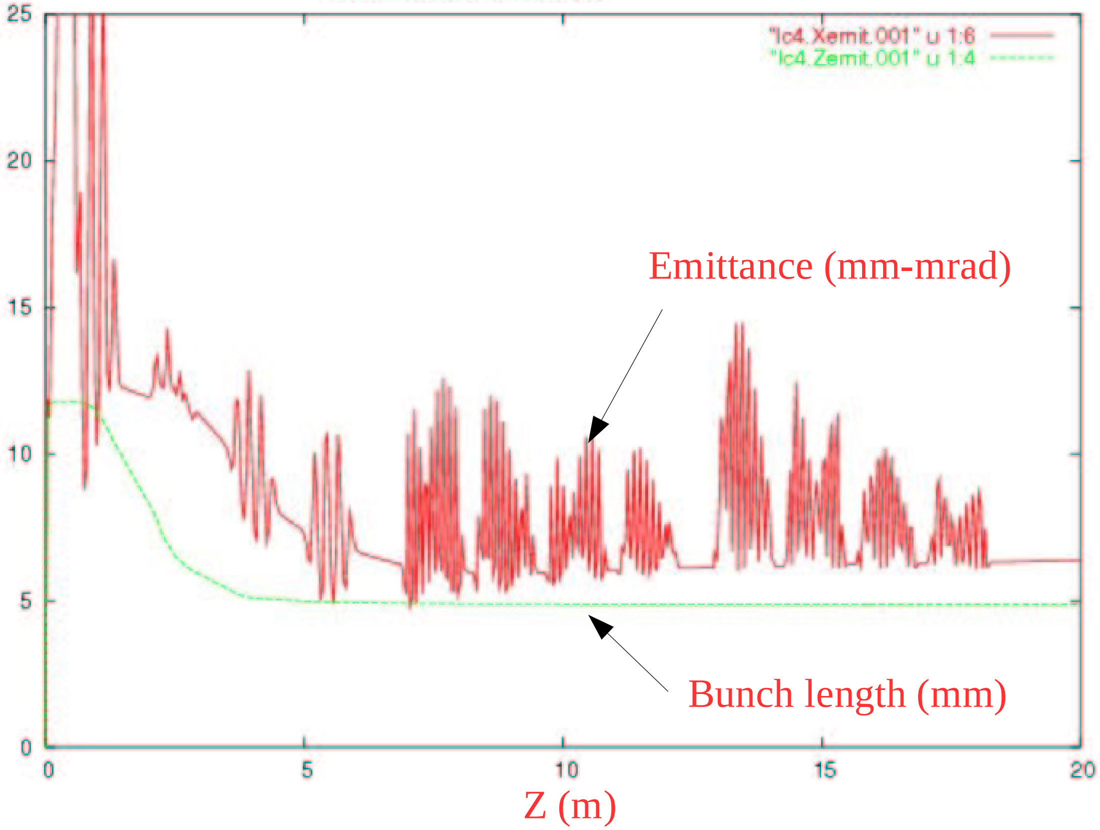
➢To achieve high quality beam Photo-emission DC-gun with dielectric coating (can produce up to 25 MV/m) [simulated the canonical 1 mm-mrad for 1 nC bunch for ERL *Bazarov/Sinclair private communication*]

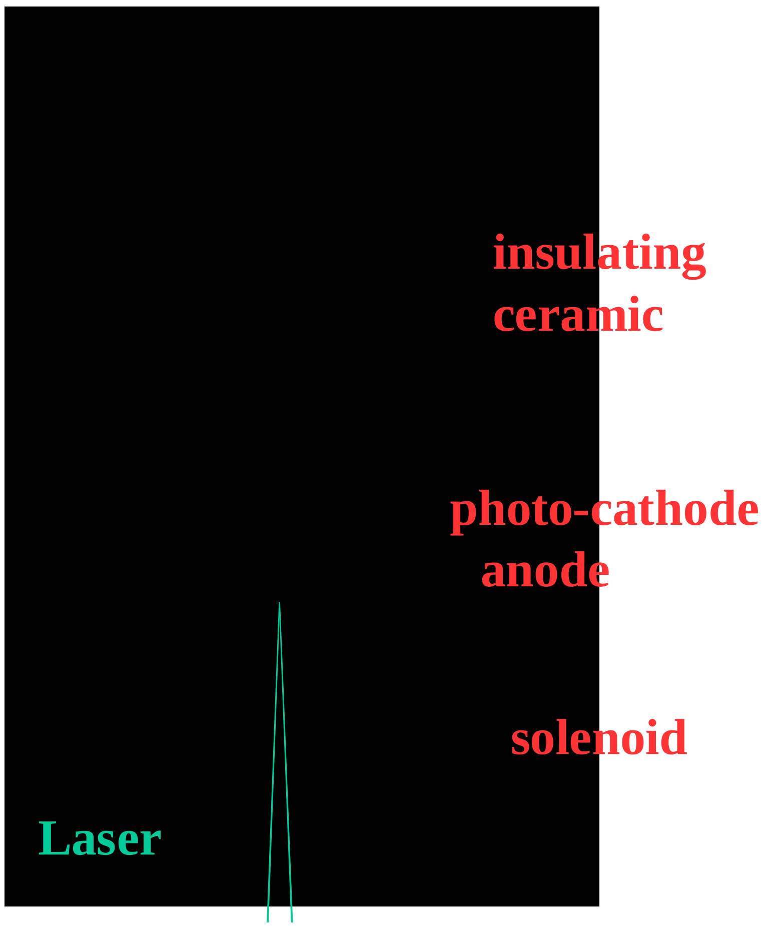
➢Operating in high vacuum quality rf-gun PWT-type (SLAC proposal) or N-cooled gun (FNAL)

Spin polarized beam issues based on DC-gun



- Anticipated performance of DC-gun ~ 25MV/m on cathode
- Example of preliminary optimization of a DC-based photoinjector (25 MV/m). Q=3.2 nC, B-field on cathode 0.12 T, consistent with production of flat beam



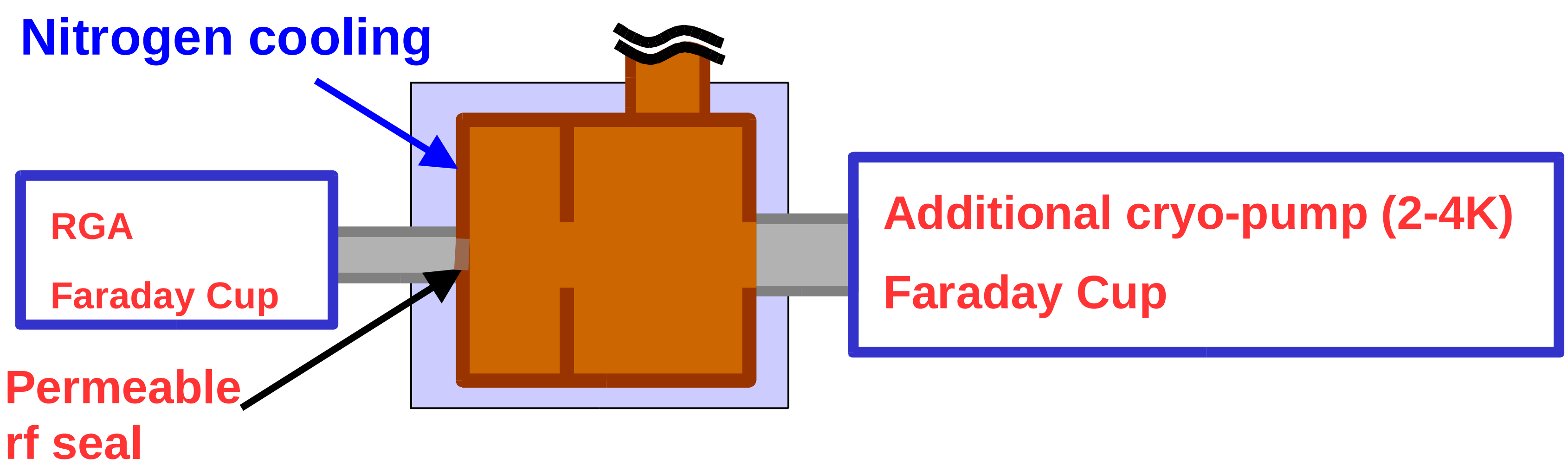


R & D for polarized rf-gun

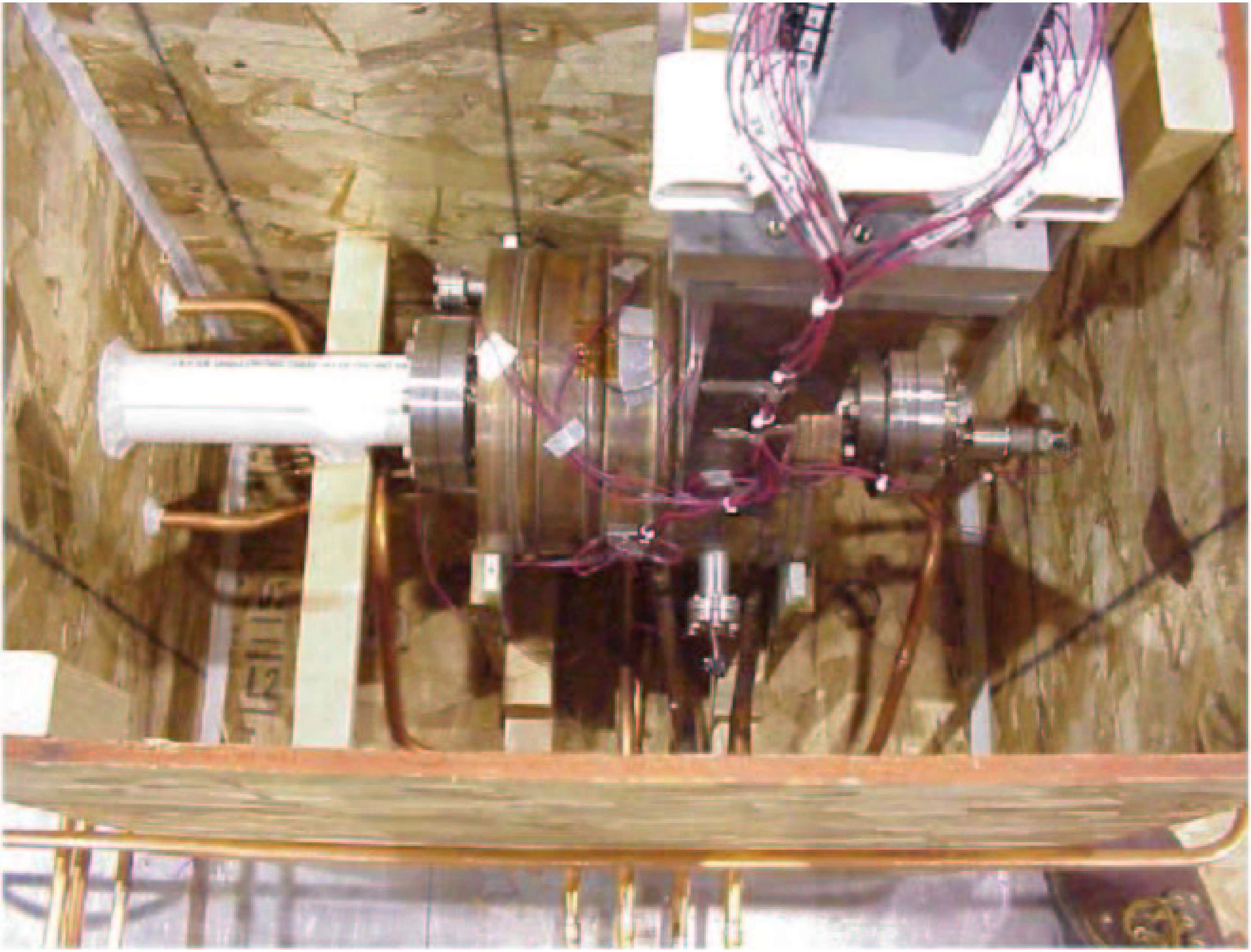
✔Improve rf-gun to enable generation of polarized beams:

- Vacuum pressure $<10^{-12}$ Torr
- GaAs photocathode in rf-gun
- lifetime and dark current studies

✔Use spare rf-gun to explore the use of cryogenic N-cooled cavity

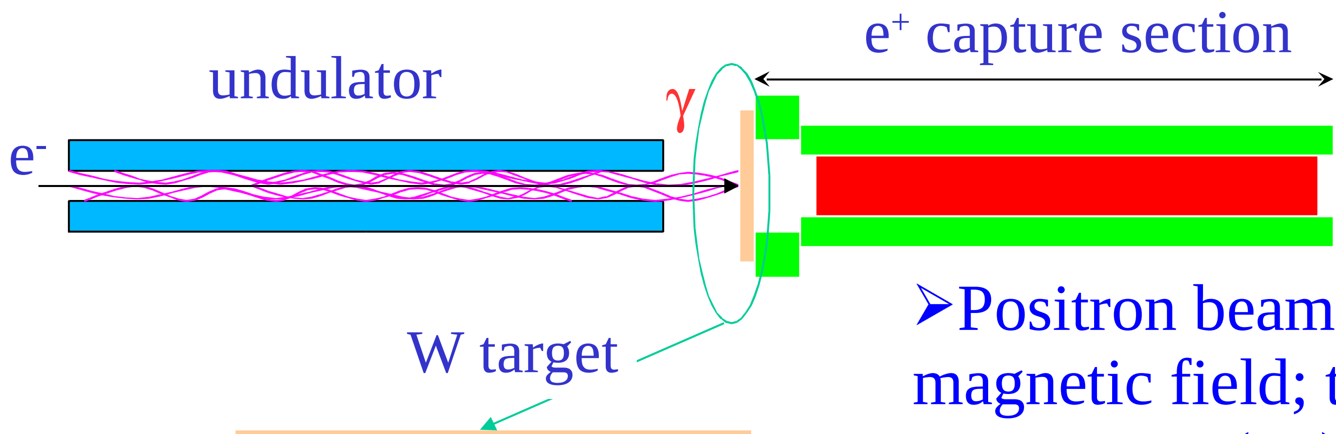


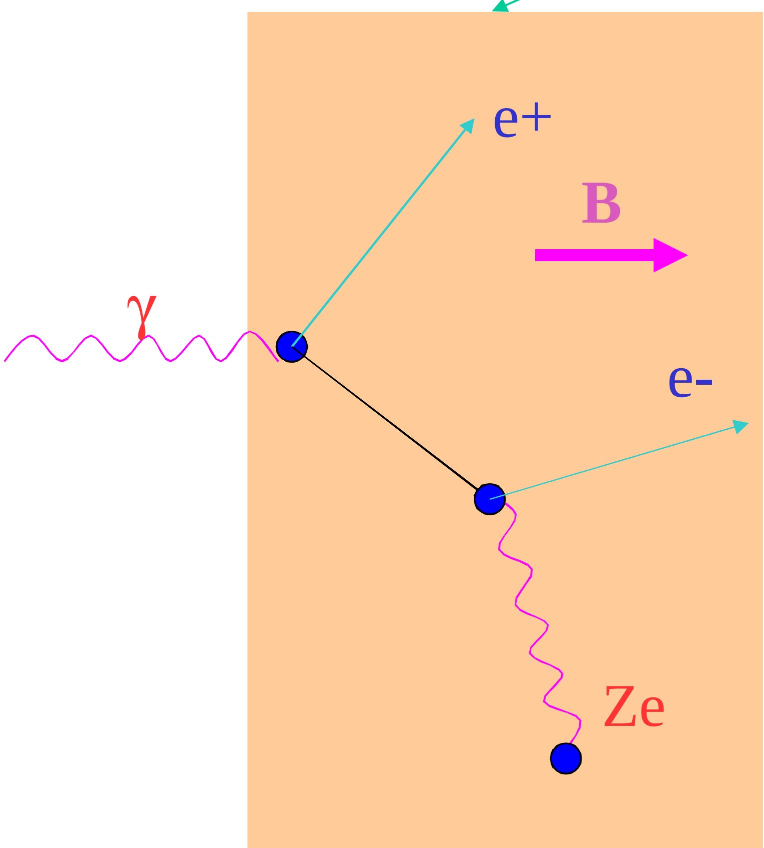
(M. Huening, EPAC 2004)



(Courtesy of M. Huening)

Positron production...





- Positron beams are generated in a magnetic field; they have an angular momentum (*2L*)...

$$L = \frac{e B_z \sigma_c^2}{2 m_e c} \simeq 293.5\, B_z [T] \sigma_c^2$$

- But transverse "thermal" emittance of positron $\gamma \varepsilon_{th} = \gamma \sigma_c \sigma'_c$ is huge

- Typically $\gamma \varepsilon_{th} \simeq 0.01\, m - rad$ while $\gamma L \simeq 0.02\, m - rad$ the beam is not angular-momentum-dominated

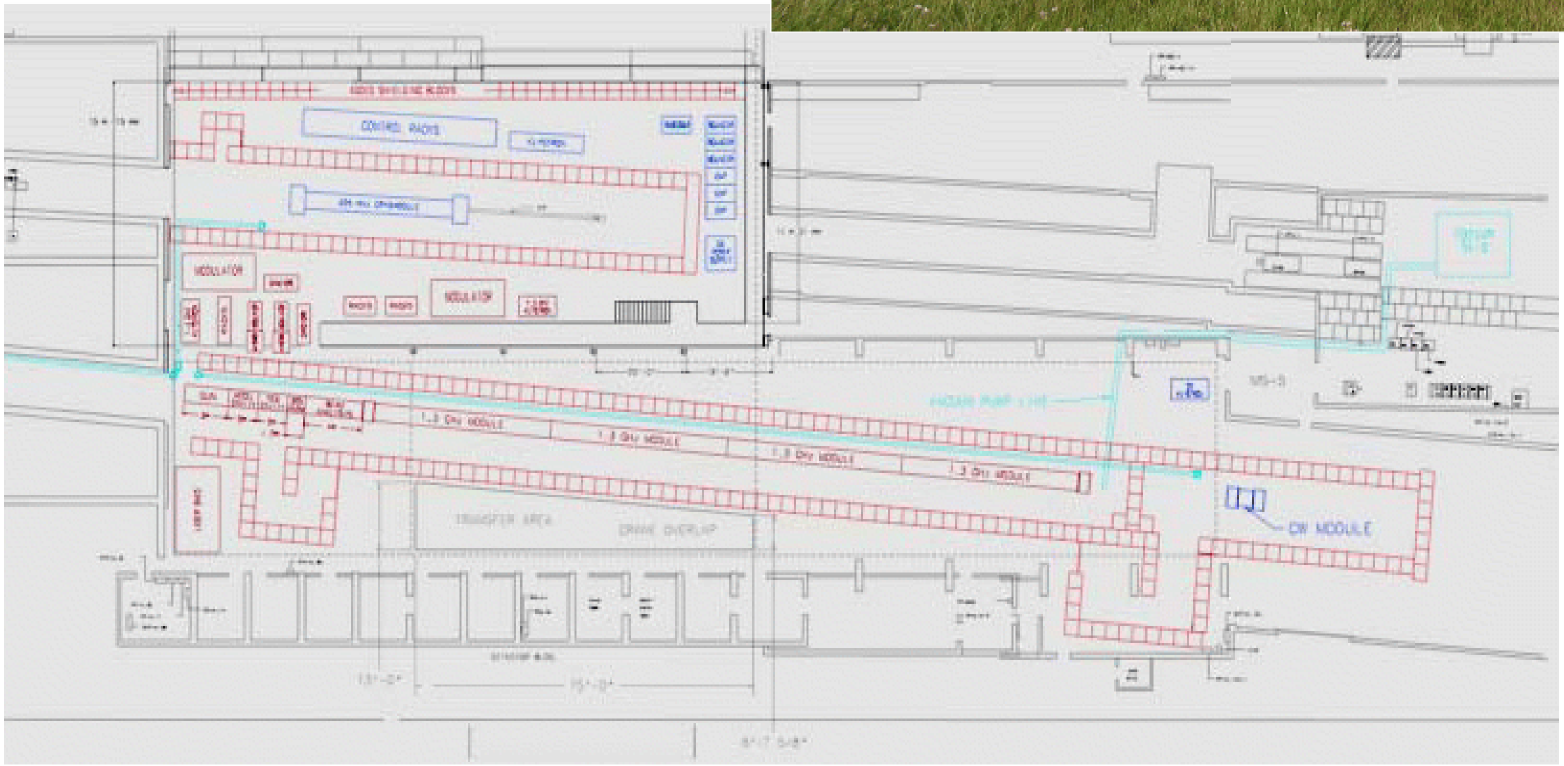
- Positron source produce highly correlated beams

Superconducting Module & Test Facility (SM&TF)

➢ US collaboration is looking in a possible test facility

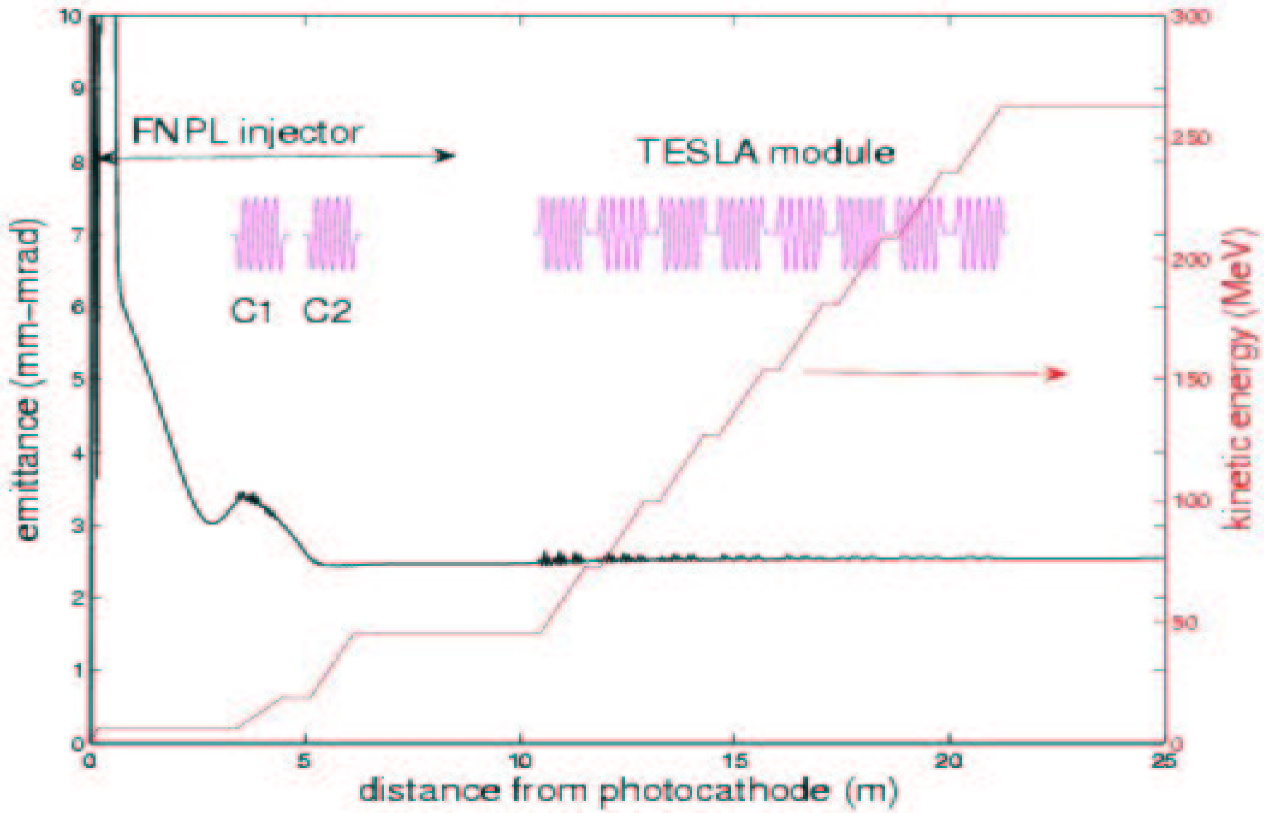
➢Eventually would include an e- injector (FNPL) and TESLA rf-units (3 acc. modules)

➢ Possible site at FNAL



Superconducting Module & Test Facility (SM&TF)

- Phase 1 of SM&TF with beam consists of:
  - FNPL (as an e- source)
  - one TESLA surperconducting module (8 cavities)
- Anticipated energy ~ 250 MeV
- Subsequent phases of the project: add cryomodule to increase energy

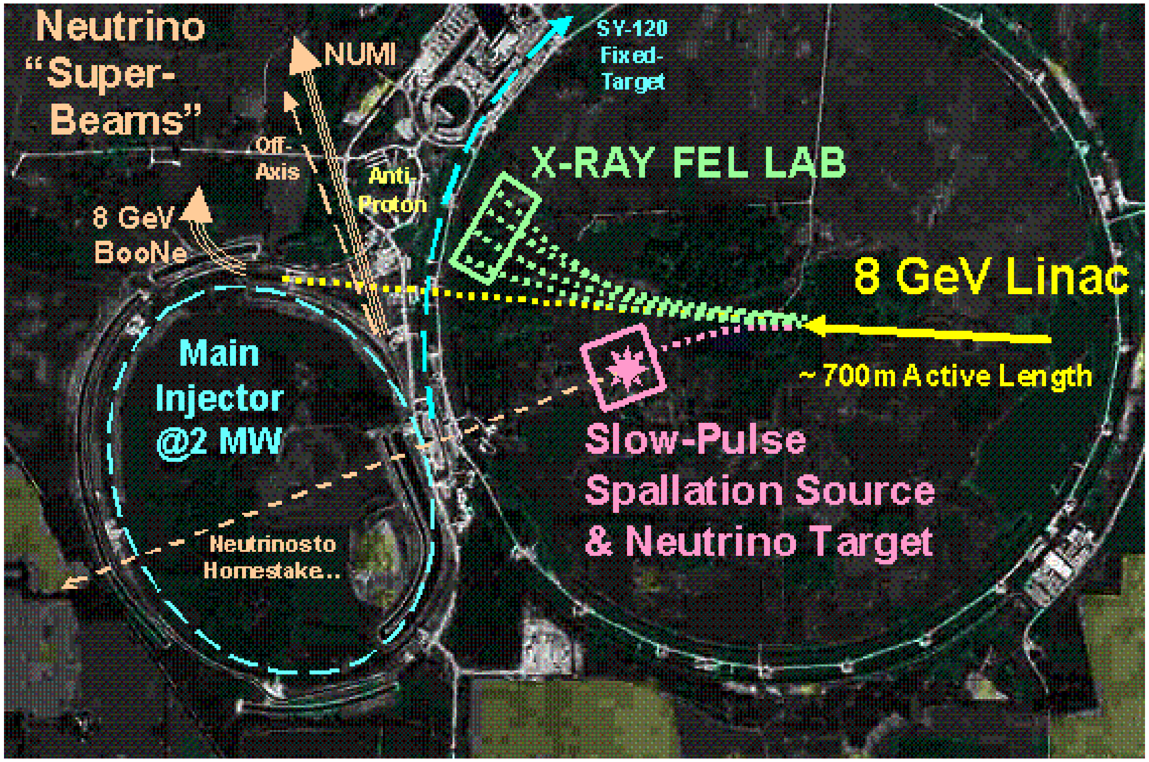


Superconducting Module & Test Facility (SM&TF)

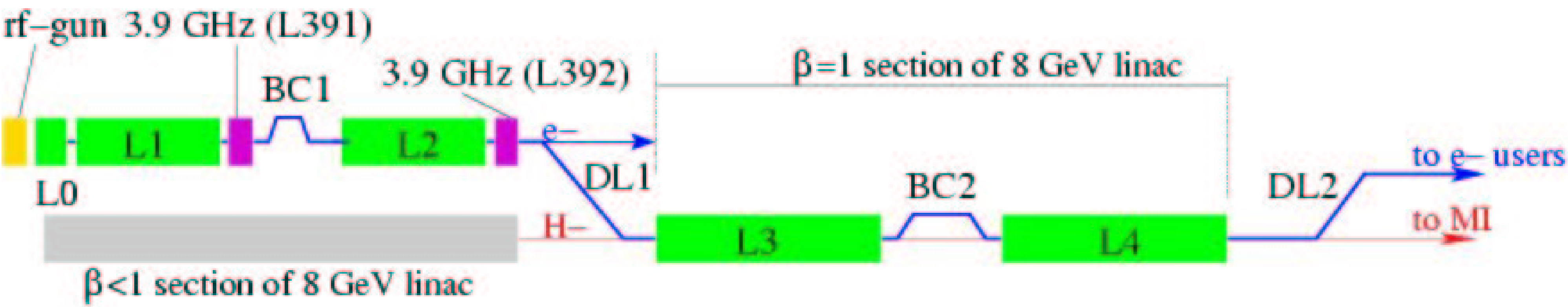
- High energy will offer opportunity for new experiments:
  - novel light source based on Smith-Purcell effects,
  - development of beam diagnostics
  - laser acceleration in vacuum

- Possible test connected to linear collider include:
  - round-to-flat beam transformation at high energy
  - optimization of round beam injector parameters
  - possible study and optimization of e+ conventional (e- on W-target) [need 500 MeV for this]

Possible use of SM&TF as e- injector for the 8GeV linac



- ➢Proposed 8 GeV H- linac could be used to accelerated electron
- ➢Preliminary simulations indicate beam parameter similar to state-of-art light source proposal (LCLS) can be achieved



(P. Piot, W. Foster, EPAC 2004)

Summary

- FNPL has supported various e- beam experiment: fundamental beam dynamics and advanced accelerator physics

- Some of the pionnering experiments (flat beam production) could have a strong impact on linear collider design

- Though FNPL reliability is still an issue... **;-(**

- FNPL upgrade planned autum 2005, will provide 40-50 MeV electron beam

- The injector will then be moved to SM&TF complex and used as an injector to produce > 200 MeV e- beam

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